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STUDYING JOINTS IN CONCRETE PAVEMENT

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The reports of research published in this magazine are necessarily qualified by the conditions of the tests from which the data are obtained Whenever it is deemed possible to do so, generalizations are drawn from the results of the tests; and, unless this is done, the conclusions formulated must be considered as specifically pertinent only to described conditions.

In This Issue

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JOINTS AND CRACKS IN CONCRETE PAVEMENTS

A COOPERATIVE STUDY BY PUBLIC ROADS ADMINISTRATION AND THE MICHIGAN STATE HIGHWAY DEPARTMENT

Reported by **EARL C. SUTHERLAND**, Senior Highway Engineer

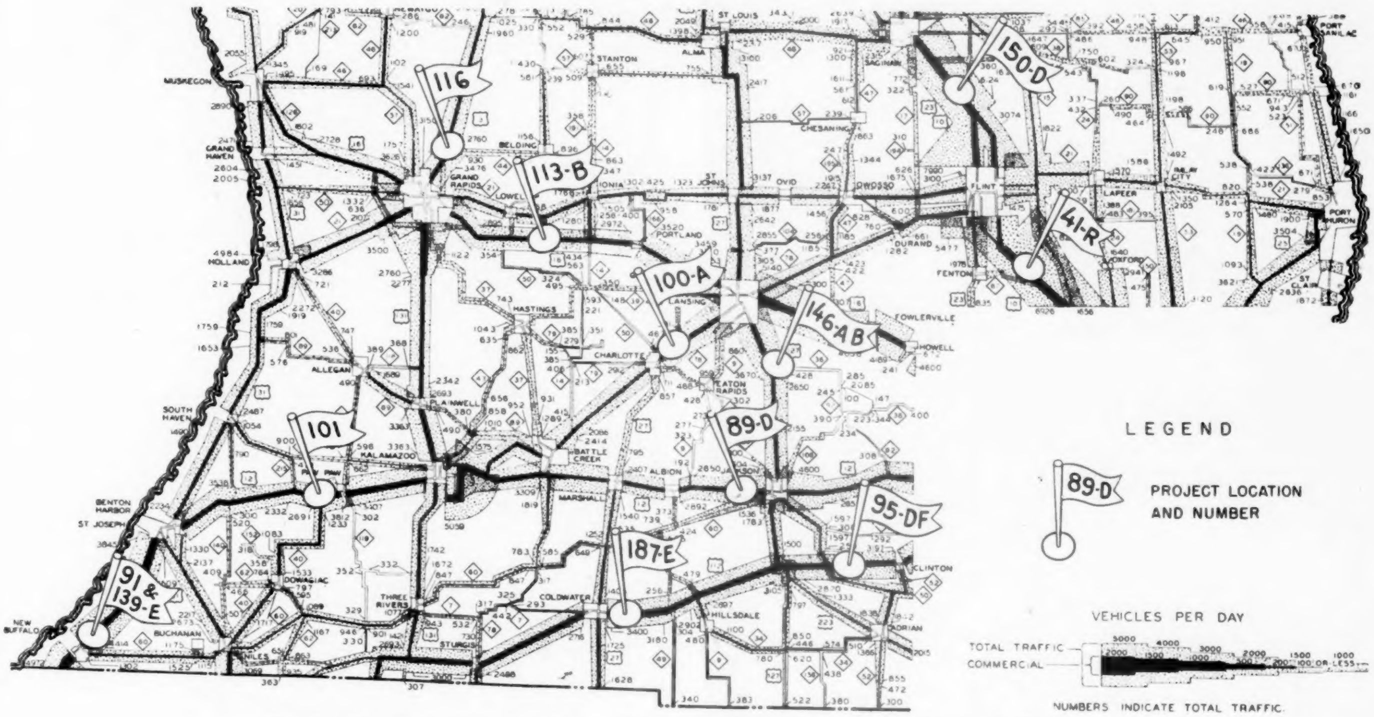

FIGURE 1.—LOCATION OF PROJECTS STUDIED AND AVERAGE TRAFFIC VOLUME.

DURING THE SUMMER OF 1938 a cooperative study was undertaken by the Michigan State Highway Department and Public Roads Administration, primarily to develop information concerning the condition of transverse joints in concrete pavements in which the joints had been constructed without provision for load transfer. Michigan has in its highway system a number of such pavements that have been in service for a long period of time, some of which carry relatively heavy traffic.

The selection of projects to be included in this study was made after a preliminary survey of the concrete pavements in the southern part of the State.[1] The majority of the projects included are approximately 10 years old and all of them have been subjected to comparatively heavy traffic during the entire period. The numbers and locations of the projects studied are shown on the accompanying traffic map, figures 1 and 2, which also indicate the average 24-hour daily commercial traffic flow. The traffic survey data from which this map was made were collected between January 20, 1936, and January 15, 1937.

General information concerning the projects and certain features of design of the pavement slabs are given in table 1. Special features of design of some of the projects are shown in table 2. The two tables should be considered jointly.

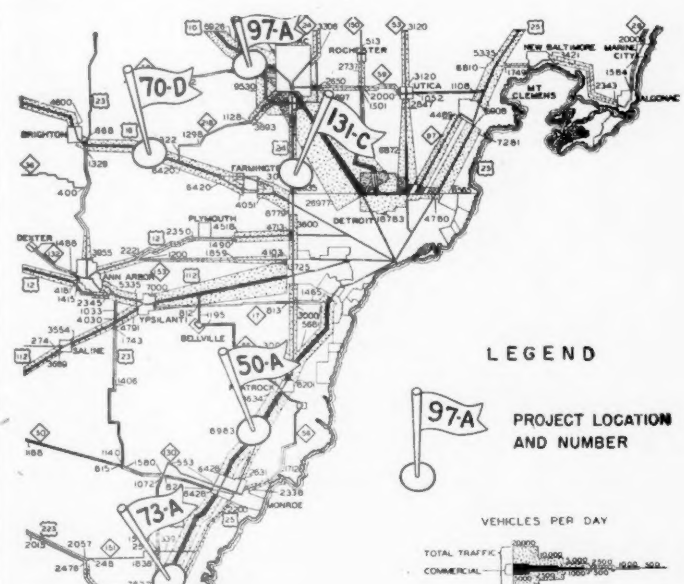

FIGURE 2.—LOCATION OF PROJECTS STUDIED IN VICINITY OF DETROIT AND AVERAGE TRAFFIC VOLUME.

[1] The preliminary survey was made by H. C. Coons of the Michigan State Highway Department, together with L. P. Scott, A. F. Haelig, L. W. Teller, and E. C. Sutherland of Public Roads Administration. The subgrade survey was made by A. E. Matthews, Assistant Engineer of Soils, Michigan State Highway Department. The crack survey was made by G. A. Mansfield, Assistant Research Engineer, Michigan State Highway Department. The joint measurements and general observations were made by A. F. Haelig, Senior Highway Engineer, and E. C. Sutherland, Senior Highway Engineer of the Public Roads Administration.

TABLE 1.—*Description of the projects*

Federal-aid project number	County	US route number	Year built	Length	Width	Cross section [1]	Sections studied, station to station	Reinforcement and edge bars	Expansion joints design data	Load transfer	Contraction joints	Longitudinal joints
				Miles	*Feet*	*Inches*						
100-A	Eaton	27	1925	5.3	20	9-7-9	82+00—134+92 162+09—217+89 269+96—324+33	(2)	1 inch at 100 feet	Station 111+20—340+100, ¾-inch bar at each edge. None 66+00—111+20.	None	Deformed metal plate. Tie bars, 5-foot spacing.
113-B	Ionia	16	1926	12.0	20	9-7-9	1402+42—1455+70 1613+87—1666+83 1881+12—1934+44	None	do	None	do	Do.
116	Kent	131	1924	4.4	20	7	14+30—110+23 170+38—223+43	3/4-inch edge bars, continuous	¾ inch at 50 feet	Edge bars continuous	do	Do.
101	Van Buren	12	1924	8.4	20	8 9-7-9 8	90+50—143+43 226+67—279+44 336+83—390+54	(2)	¾ inch variable	Edge bars continuous in certain sections.	do	Do.
139-E	Berrien	12	1931	2.5	40	9	70+50—176+00	Reinforced throughout with 60-pound wire fabric.	1 inch at 100 feet	None	do	(2)
91	do	12	1923	1.3	18	8	0+00—53+66	¾-inch edge bars	None		do	Deformed metal plate. Tie bars, 5-foot spacing.
91 [3]	do	12	1931	1.3	22	9	0+00—53+66	Reinforced throughout with 60-pound wire fabric.	1 inch at 100 feet	None	do	(2)
89-D	Jackson	12	1924	5.7	20	8	1260+37—1313+30 1371+71—1425+05 1475+99—1529+44	None	¾ inch at 100 feet	do	do	Deformed metal plate. Tie bars, 5-foot spacing.
95-D F	Lenawee	112	1926	13.5	20	9-7-9	1140+52—1193+51 1275+04—1328+13 1500+93—1553+90	do	1 inch at 100 feet	do	do	Do.
73-A	Monroe	24	1925	5.5	20	10-8-10	64+79—141+54 198+25—278+26	do	do	do	do	Deformed metal plate. Tie bars, 30-inch spacing.
73-A [3]	do	24	1935	5.0	11	10-8-10	64+79—141+54 198+25—278+26	Reinforced throughout with 60-pound wire fabric.	1 inch at 50 feet	Translode	50-foot spacing.	None. [4]
50-A	do	24	1923	8.7	20	9	238+64—291+78 400+67—453+53 606+15—658+80	¾-inch edge bars and special [2]	Variable spacing. Width not known.	None	None	Deformed metal plate. No tie bars.
50-A [3]	do	24	1933	8.4	20	10	238+64—291+78 400+67—453+53 606+15—658+80	Reinforced throughout with 60-pound wire fabric.	1 inch at 100 feet	do	do	None. [5]
70-D	Oakland	16	1925	6.4	20	8	280+04—383+56 501+37—553+98	¾-inch edge bars and special [2]	do	Edge bars continuous	do	Deformed metal plate. Tie bars, 6-foot spacing.
70-D [3]	do	16	1932	10.4	10	10	280+04—383+56 501+37—553+98	Reinforced throughout with 60-pound wire fabric.	1 inch at variable spacing.	None	do	None. [4]
131-C	do	24	1930	8.6	20	10	122+50—173+43 285+23—334+65 478+56—531+49	Part of pavement reinforced [2]	1 inch at 100 feet	do	do	Deformed metal plate. Tie bars 40-inch spacing.
97-A	do	10	1924	4.7	20	9-7-9	250+20—346+49 366+27—429+26	None	¾ inch at 100 foot	do	do	Deformed metal plate. Tie bars, 5-foot spacing.
97-A [3]	do	10	1928	4.7	20	10-8-10	250+20—346+49 366+27—429+26	Part of pavement reinforced [2]	1 inch at 100 feet	do	do	None. [5]
41-R	do	10	1931	10.0	40	10	715+00—769+00 917+00—970+00 1084+98—1138+00	Reinforced throughout with 60-pound wire fabric.	¾ inch at 50 feet	do	do	Bulkhead. Butt joint. [2]
150-D [3]	Genesee	10	1932	4.0	20	10	295+40—375+84 419+27—498+89	do	1 inch at variable spacing.	do	do	None. [5]
146-B	Ingham	127	1925	4.0	20	9-7-9	326+57—484+79	None	do	do	do	Deformed metal plate. Tie bars, 5-foot spacing.
187-E	Branch	112	1918	1.4	16	6-8-6	1017+25—1066+68	do	1 inch± at variable spacing.	do	do	None.

[1] A single dimension indicates uniform thickness.
[2] See table 2.
[3] Widening.
[4] Single lane abutted against 1 side of old pavement. No connection between old and new pavements.
[5] Single lane abutted each side of old pavement. No connection between old and new pavements.

TABLE 2.—*Special design features of various projects*

Federal-aid project No.	Special design features
100-A	¾-inch diameter edge bars, continuous across the joints: 111+20—340+00 Special reinforcement. Longitudinal steel; ten ½-inch diameter round at variable spacing: 66+00—111+20
101	¾-inch diameter edge bars, continuous across joints: 74+00— 96+00 126+00—199+54 337+80—445+00 Special reinforcement. Longitudinal steel; ½-inch diameter round, 24-inch spacing. Transverse steel; ½-inch diameter round, 28-inch spacing: 0+00— 8+50 15+00— 74+00 96+00—126+00 Longitudinal steel; ½-inch diameter round, 36-inch spacing. Transverse steel; ½-inch diameter round, 15-inch spacing: 8+50—15+00
139-E	The longitudinal joint at the center of the 40-foot pavement is of the straight-butt type. Tie bars at intervals of 20 inches were placed across this joint on the fill sections. No tie bars were used elsewhere. The longitudinal joints 10 feet from each edge of the pavement are of the weakened-plane type. No tie bars were used across these joints.
91	22-foot widening abutting old pavement. Longitudinal joint in the widening is of the weakened-plane type. No tie bars were used across this joint.
73-A	Load transfer provided across expansion joints in new pavement.
50-A	Special reinforcement in old pavement. Transverse steel; ¾-inch round, 12½-foot spacing.
70-D	Special reinforcement in old pavement. Longitudinal steel; ½-inch round, 6, 42, and 78 inches from free edges. Transverse steel; ½-inch diameter round, 15-inch spacing: 284+25—284+70 435+95—436+25 287+00—295+00 444+00—465+00 298+50—299+25 527+00—527+30 316+25—316+55 535+40—535+70 328+25—328+55 553+60—553+90 334+00—344+00 515+70—516+72 347+20—347+50 420+50—422+50 365+60—365+90 465+00—494+00 393+20—393+50 614+00—616+00 412+60—412+90
131-C	Special reinforcement. Wire fabric (60 pounds per square): 77+80— 84+07 366+50—422+00 84+12—104+00 543+00—559+00 135+00—144+00 598+00—607+00 156+00—166+00 617+00—627+50 310+00—336+05
97-A	Special reinforcement in widening. Wire fabric (60 pounds per square): 91+88—101+90 199+44—207+00 214+51—223+50 278+18—281+36
41-R	Tie bars across longitudinal joints. ½-inch diameter round, 48 inches long, 40-inch spacing: 664+50—669+50 928+00— 995+00 674+50—681+00 1000+00—1013+00 689+50—696+00 1018+00—1057+00 699+50—728+00 1061+00—1070+50 733+00—735+50 1082+50—1100+00 738+00—739+50 1104+50—1108+00 742+50—767+00 1110+50—1115+50 791+50—809+50 1119+00—1145+06 812+50—833+00 1152+00—1157+00 837+00—847+00 1163+50—1166+50 850+00—857+50 1170+00—1173+50 870+50—887+00 1177+00—1191+28 892+00—918+00

REPRESENTATIVE SECTIONS OF PROJECTS EXAMINED IN DETAIL

The majority of the projects were of such length that it was impracticable to make a detailed study of the entire project. For this reason, 3 representative miles were selected for study on all projects exceeding 3 miles in length. Where the total length of the project was less than 3 miles, the entire pavement was examined. The combined total length of all of the projects studied is approximately 110 miles. Of this, 46 representative miles were actually surveyed in detail.

Certain subgrade data had been collected on some of the projects prior to this survey. These were supplemented by additional data obtained in a subgrade survey made as a part of the study. A complete subgrade survey was made on all projects where there had been no earlier survey. The data obtained permitted the general classification of the soils encountered but gave no indication of the density or of the moisture content of the subgrade beneath the pavement. On

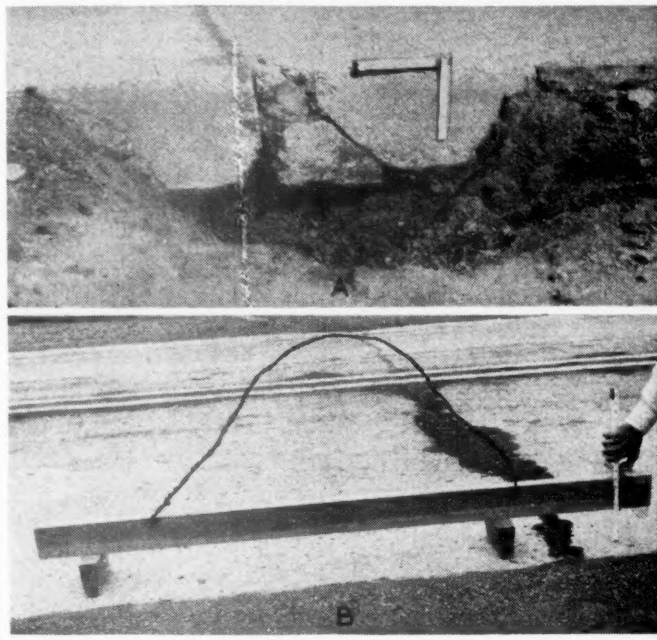

FIGURE 3.—A, SHOULDER REMOVED FOR INSPECTION OF EXPANSION JOINT; B, DEVICE FOR MEASURING FAULTING AT JOINTS AND CRACKS.

some of the projects several crack surveys had been made previously and, in such cases, the earlier crack surveys were simply brought up to date. On the remainder of the projects a complete crack survey was made for the section being studied.

On all projects a detailed study was made of the joints in the course of which the following observations were made: (1) The width of opening of the joints and whether these openings were clear or filled; (2) The differences in elevation of the pavement surface on the two sides of the joint. These measurements were made at certain cracks, also; (3) The general condition of the joint, that is, whether or not it was spalled, broken, etc.

While the main object of the investigation was to study joints, it was thought desirable to make, in addition, a rather close examination of the general condition of the pavements and this developed a considerable amount of information not directly connected with joints.

Figure 3, A shows the method of exposing the joints for study. It was not practical to expose all of the joints as shown, but this was the general procedure followed. Some joints were examined in more detail than others.

Since it was desired to measure the difference in elevation or faulting at a large number of joints and cracks, it was necessary to devise a method permitting determination to be made quickly yet accurate enough for the purpose. Great precision was not justified because of the roughness of the concrete surfaces. The device used is shown in figure 3, B. The blocks that rested on the concrete were 4 feet apart and were always placed on the slab over which traffic approached the joint. The block nearest the joint was placed a foot or so back from it so that the local irregularities at the joint would not affect the measurements. Also the faulting measurements were made 4 or 5 inches from the joint for the same reason. The differences in elevation with respect to the arbitrary datum thus established were measured to the nearest one-sixteenth inch

TABLE 3.—*Summary of traffic survey data* [1]

Federal-aid project No.	Average daily traffic (all vehicles)	Average daily commercial vehicles								
		Number of vehicles	Average number of wheels per vehicle	Total number of wheel loads	Wheel loads 4,000 pounds or greater	Wheel loads 6,000 pounds or greater	Wheel loads 9,000 pounds or greater	Total wheel loads 4,000 pounds or greater	Total wheel loads 6,000 pounds or greater	Total wheel loads 9,000 pounds or greater
					Percent	*Percent*	*Percent*			
100-A	3,337	476	4.74	2,256	27.92	10.14	0.61	630	229	14
113-B	2,895	420	5.08	2,134	36.38	19.28	1.30	776	411	28
116	3,118	355	4.59	1,629	22.21	7.64	.66	362	124	11
101	2,691	673	5.14	3,459	32.39	16.45	2.02	1,120	569	70
91, 139-E	4,972	1,100	5.02	5,522	33.04	16.04	.43	1,824	886	24
89-D	2,650	439	4.54	1,993	30.03	14.00	1.85	598	279	37
95-DF	2,820	700	4.93	3,451	32.24	15.99	.97	1,113	552	33
73-A	7,622	1,884	5.12	9,646	38.73	21.63	1.27	3,736	2,086	122
50-A	8,634	1,990	5.12	10,180	38.73	21.63	1.27	3,943	2,202	129
70-D	6,420	887	4.80	4,258	25.41	12.52	1.97	1,082	533	84
131-C	2,635	650	5.20	3,380	30.91	14.75	1.70	1,045	499	57
97-A	9,828	1,695	5.02	8,509	29.00	15.17	1.23	2,468	1,291	105
41-R	6,926	1,028	5.02	5.161	29.00	15.17	1.23	1,497	783	63
150-D	[illegible], 124	700	4.69	3,283	28.16	14.42	1.38	924	473	45
146-B	3,670	389	4.35	1,692	21.65	8.22	.27	366	139	5
187-E	3,400	707	4.93	3,486	32.24	15.99	.97	1,124	557	34

[1] The basic data were collected by the Michigan Highway Planning Survey between January 1936 and January 1937.

TABLE 4.—*Subgrade classification*

Federal aid project No.	Mile surveyed	Subgrade soil group	Soil series	Special subgrade conditions within the area surveyed
100-A	1	A-6	Maimi and Conover	Subgrade rests on unstable peat between stations 162 and 167.
	2	A-6	do	
	3	A-6	do	
113-B	1	A-6	Napanee with small areas of Miami and Brookston	A sand and gravel subbase with stone or gravel bleeders was placed between stations 1427+20 and 1455; 1628+80 and 1660.
	2	Mainly A-6	Napanee and Miami with small areas of Coloma	
	3	Mainly A-6	Miami and Conover with small areas of Brookston	
116	1 and 2	A-3	Firdst ¾ mile Fox and Warsaw (outwash area). Remaining 1¼ miles uniform Bellefontaine and Coloma.	A 4-inch sand subbase was placed between stations 171 and 173+50; 177+50 and 180; 190+97 and 225.
	3	A-3, A-6	Coloma to Isabella	
101	1	Mainly A-3	Variable—Plainfield, Berrien, Brookston, Coloma	The water table is near the surface between stations 111 and 133 and an 8-inch gravel subbase was placed between stations 129 and 134+61.
	2	A-3	Mianly Fox and Plainfield	
	3	A-3	Fox and Plainfield	
91 and 139-E	1	A-3	Bridgman, Newton, and Plainfield	The water table is near the surface between stations 12 and 15. The fill settled between stations 145 and 148.
	2 and 3	A-3	Variable—Plainfield, Berrien, Ottawa, Saugatuck	
89-D	1	A-3	Fox	
	2	A-6	Hillsdale	
	3	A-3, A-6	Hillsdale except last 1,500 feet which is Oshtemo and Plainfield.	
95-DF	1	A-3, A-6	Mainly Miami with some Coloma	The surface relief is generally rolling with deep cuts and high fills.
	2	A-3	Mainly Bellefontaine and Coloma	
	3	A-3	Variable—mainly Fox with some Napanee, Plainfield, and Hillsdale.	
73-A	First 1.5	A-6, approaching A-7	Brookston, Brown Napanee	This pavement is on an old lake bed and the surrounding area is very flat. A large part of the old pavement is laid on a 6- to 10-inch well-drained sand and gravel subbase.
	Second 1.5	A-3, A-6	Mainly Brown Napanee with some Brookston and Hillsdale.	
50-A	1 and 2	A-6, approaching A-7	Brown Napanee	This pavement is in the same area as project 73-A and the subgrade is of the same type except no subbase was used.
	3	do	Mainly Brown Napanee with small area of Genesee	
70-D	1, 2, and 3	A-6	Miami and Conover	The fill has settled between stations 364 and 366.
131-C	1	A-3	Newton, Gilford, Berrien, and Ottawa	Tile edge drains backfilled with gravel were placed between stations 133 and 144; 158 and 165; 517 and 524.
	2	A-6	Napanee, Brookston, Allendale, and Conover	
	3	A-3, A-6	Miami and Bellefontaine	
97-A	First 1.8	A-3	Mainly Fox and Oshtemo	The fill has settled over an unstable peat area between stations 278 and 281.
	Second 1.2	A-3 predominant	Mainly Fox and Oshtemo with some Miami and Bellefontaine.	
41-R	1	A-3, A-6	Miami and Bellefontaine	The fill has settled tc some degree between stations 761+50 and 763+25; 935+50 and 937+25.
	2	A-6	Miami	
	3	A-3, A-6	Mainly Miami with some Bellefontaine	
150-D	First 1.5	A-6	Miami, Conover, Brookston with some Bronson	
	Second 1.5	A-3, A-6	Variable—Ottawa, Berrien, Brady, Bronson, Newton, Allendale, Brookston, and Conover.	
146-B	1, 2, and 3	A-3, A-6	Variable—Miami, Conover, Hillsdale, Newton, Maumee, Bellefontaine, and Oshtemo.	A large part of this pavement is on a sandy fill over poorly drained muck. The pavement has settled between stations 344+10 and 347+21; 398+10 and 401+10, 409+82 and 410+93; 419+70 and 419+90.
187-E	1	A-1, approaching A-3	Warsaw	

in the manner shown. The measured differences are not necessarily true differences in elevation but are, rather, the departure at a given point on the slab beyond the joint from the datum established by the surface of the approach slab. The measurements were made perpendicular to the surface of the pavement rather than in a true vertical direction. It is thought that this measured difference is best described as "faulting" at the joint and this term will be used hereafter. Measurements of faulting were made at a sufficient number of joints and cracks so that errors caused by the occasional irregularities of the concrete surface would be largely eliminated in the averages.

General observations were made of the condition of the joints, cracks, and the condition of the pavement as a whole and a number of photographs were made.

A summary of the traffic data on the various sections is given in table 3. The average daily traffic is shown in the second column, while the average daily commercial traffic is shown in the third column. In the last three columns the commercial traffic is divided into three wheel-load weight classes.

Certain subgrade survey data for the different sections are shown in table 4 (*4*).[2] Michigan uses the "soil series" method of soil classification in highway work.

[2] Italic numbers in parenthesis refer to bibliography, p. 205.

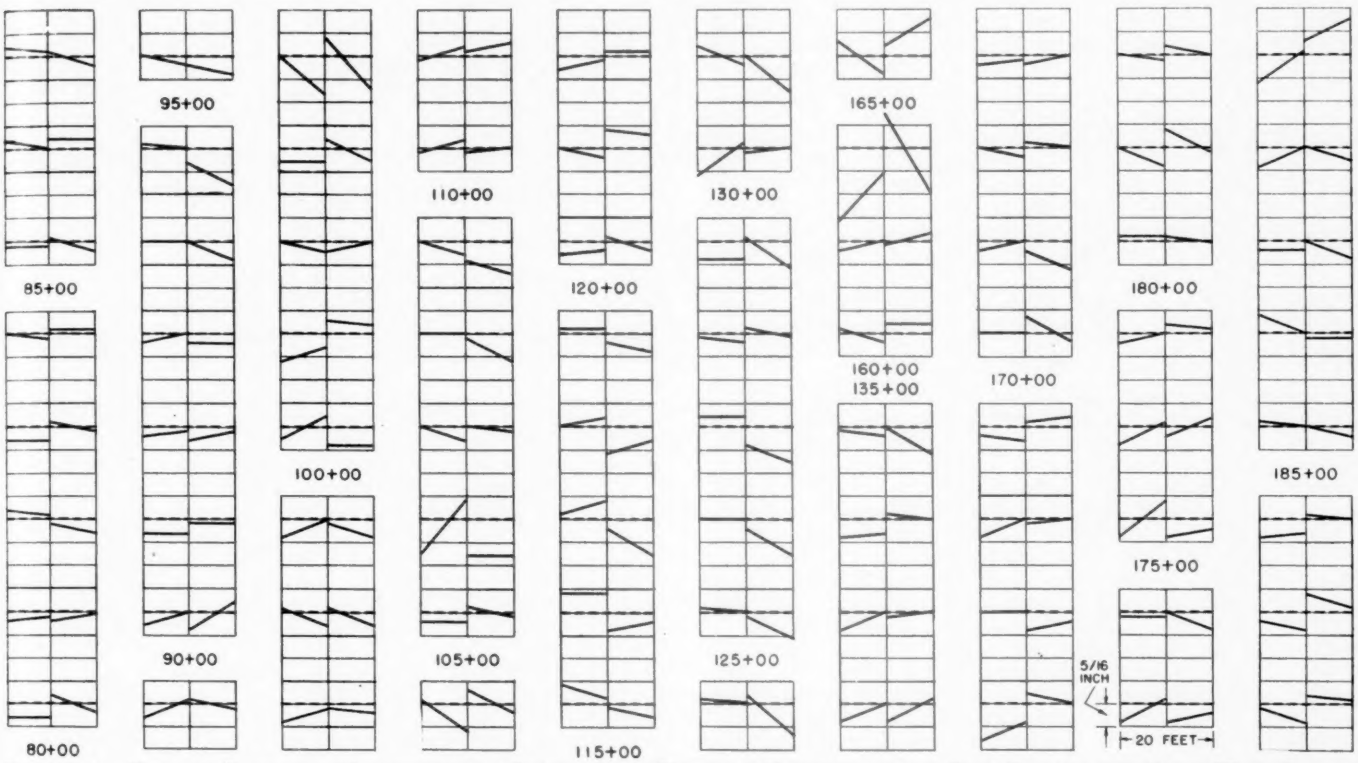

FIGURE 4.—TYPICAL FAULTING MEASUREMENTS SHOWING THE VERTICAL POSITION OF THE SLAB BEYOND THE JOINT WITH RESPECT TO THE APPROACH SLAB IN THE DIRECTION OF TRAFFIC.

With the following exceptions, the concrete in the pavements examined contained silicious gravel as the coarse aggregate: (1) The widening on project 50–A; (2) the original pavement of project 73–A; and (3) in part of the pavement of project 95–DF. In these three sections crushed stone coarse aggregate was used.

GENERAL CONDITION OF INDIVIDUAL PROJECTS DESCRIBED

Project 100–A.—This two-lane pavement was 13 years old at the time of the survey. In general, slab length varied between 16 and 28 feet and over the whole project averaged less than 20 feet. The pavement was rough over small areas where the subgrade had settled. In general, there was no unusual amount of spalling or breakage at the transverse joints. A large percentage of the cracks were open and many of them were badly spalled and disintegrated.

Project 113–B.—This two-lane pavement was 12 years old at the time of the survey. The slab length varied generally between 12 and 18 feet and averaged 14 feet. The joints were generally in good condition and there was only a moderate amount of spalling at the cracks.

Project 116.—This two-lane pavement was 14 years old at the time of the survey. The average slab length in the first 2 miles, with the sand and gravel subgrade, was approximately 18 feet, while that in the third mile, where the less desirable subgrade is found was approximately 16 feet. The 4-inch sand subbase, in certain areas, appeared to have had little, if any effect on the amount of cracking.

The joints were generally in good condition. The cracks in the first 2 miles were closed and very little spalling had occurred. The cracks in the third mile were open slightly and a greater degree of spalling had taken place.

Project 101.—This two-lane pavement was 14 years old at the time of the survey. The water table was relatively close to the surface in the first mile and this appears to have caused considerable cracking from frost action. The average slab length in this mile ranged generally from 10 to 20 feet. The gravel subbase and special reinforcement in parts of this mile appear to have had little if any effect on the amount of cracking. The average slab length in the second and third miles was greater than that in the first mile, ranging generally from 15 to 35 feet. A large percentage of the cracks in the first mile were open and badly spalled, but generally the cracks in the second and third miles were in better condition. There was a moderate amount of spalling at the joints. Considerable scaling, especially in the first mile, had occurred at the intersection of the cracks and longitudinal joint.

Project 139–E.—This four-lane reinforced pavement was 7 years old at the time of the survey. It was in much better condition than most of the other pavements examined. The slab lengths varied generally between 40 and 80 feet and the average slab length was 47 feet. The great majority of the cracks were closed and practically no spalling or disintegration had occurred at the joints, cracks, or other parts of the pavement. While the fact that this pavement is only 7 years old is no doubt responsible to some degree for its good condition, it is probable that the favorable subgrade conditions and the presence of welded fabric reinforcement have also been important contributing factors.

Project 91.—This was originally a two-lane pavement built in 1923. Two additional lanes were added at one side of the old pavement in 1931. The original pavement was plain concrete and the new pavement was reinforced with welded fabric. Both pavements were in better condition than the majority of the other pavements of same age, and this was especially noticeable on the newer pavement. The average slab lengths of the

TABLE 5.—*Summary of data*

Federal-aid project No.	Cross section	Year built	Average 24-hour traffic, 1936	Number of heavy wheel loads, average daily, 1936 (commercial)			Original slab length	Average slab length, 1938	Number of corner breaks at expansion joints per lane mile	Expansion joints where maximum difference in elevation of slabs was [2]—			Cracks [1] where maximum difference in elevation of slabs was [2]—			Number of transverse cracks, per lane mile [1]	
				4,000 pounds or above	6,000 pounds or above	9,000 pounds or above				¼ inch or more	⅛ inch to 3/16 inch	1/16 inch [3]	¼ inch or more	⅛ inch to 3/16 inch	1/16 inch [3]	Within 8 feet of expansion joints	Within 11 feet of expansion joints
	Inches						*Feet*	*Feet*		*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*		
100-A	9-7-9	1925	3,337	630	229	14	94	18	1	36	42	18	4	31	46	6	15
113-B	9-7-9	1926	2,895	776	411	28	98	14	1	47	35	14	8	32	41	14	35
116	7	1924	3,118	362	124	11	47	17	1	27	49	18	2	24	32	7	22
101	8, 9-7-9	1924	2,691	1,120	569	70	108	18	1	42	41	14	6	38	36	6	18
139-E	9	1931	4,972	1,824	886	24	92	47	0	11	42	31				0	1
91	8	1923	4,972	1,824	886	24	358	24	0				5	41	38		
91 [4]	9	1931	4,972	1,824	886	24	93	66	0	15	50	22				1	2
89-D	8	1924	2,650	598	279	37	88	17	1	22	48	25	2	38	39	3	12
95-D. F	9-7-9	1926	2,820	1,113	552	33	90	23	0	25	45	20	7	50	27	7	21
73-A	10-8-10	1925	7,622	3,736	2,086	122	82	15	0	30	42	16	1	37	40	14	28
73-A [4]	10-8-10	1935	7,622	3,736	2,086	122	27	26	0	2	17	46				1	2
50-A	9	1923	8,634	3,943	2,202	129	133	18	3	48	33	10	8	42	23	5	7
50-A [4]	10	1933	8,634	3,943	2,202	129	98	37	0	48	40	10				6	10
70-D	8	1925	6,420	1,082	533	84	175	16	0	32	38	18	8	44	33	5	8
70-D [4]	10	1932	6,420	1,082	533	84	92	38	0	21	46	23	0	38	36	1	2
131-C	10	1930	2,635	1,045	499	57	93	25	0	23	43	25	5	26	42	1	3
97-A	9-7-9	1924	9,828	2,468	1,291	105	91	17	1	36	42	16	7	38	33	9	23
97-A [4]	10-8-10	1928	9,828	2,468	1,291	105	99	20	0	48	40	7	2	34	34	5	12
41-R	10	1931	6,926	1,497	783	63	49	25	0	38	39	14	2	51	35	1	2
150-D [4]	10	1932	6,124	924	473	45	99	45	0	36	42	14	1	61	33	0	1
146-B	9-7-9	1925	3,670	366	139	5	90	17	0	36	40	16	5	43	38	9	18
187-E	6-8-6	1918	3,400	1,124	557	34	72	30	0	50	33	11	15	50	25	4	11

[1] Those at which measurements were made.
[2] In determining these percentages a joint or crack in a single pavement lane was considered to be a unit.
[3] Faulting less than 1/16 inch not included.
[4] Widening.

old and new pavements at the time of the survey were 25 and 66 feet, respectively. The cracks in the old pavement were open and badly spalled, but the joints and cracks in the new pavement were in good condition. It is thought probable that the favorable subgrade conditions and the presence of the distributed reinforcement were largely responsible for the limited amount of transverse cracking.

Project 89-D.—This two-lane pavement was 14 years old at the time of the survey. The slab lengths varied generally between 16 and 20 feet, but there was one area, notably between stations 1510 and 1522, where the average slab length was greater than 20 feet. The majority of the transverse cracks were open and a considerable amount of spalling and disintegration had occurred in their vicinity. The joints were in good condition except for a moderate amount of spalling at the intersection of the longitudinal and transverse joints.

Project 95-DF.—This two-lane pavement was 12 years old at the time of the survey. Much of it was badly scaled and had been covered with a thin film of bituminous material. It was necessary, for this reason, to select for the survey 3 miles which were in better than average condition. Slab lengths throughout the first mile were uniformly low and the average for the whole mile was 14 feet. Slab lengths in the second and third miles varied generally between 20 and 50 feet and averaged approximately 29 and 26 feet, respectively. A considerable amount of spalling and disintegration had occurred at the joints and cracks.

Project 73-A.—This is a three-lane pavement. The first two lanes were of plain concrete, built in 1925. The third lane was built 10 years later and is reinforced. Slab lengths on the old part of the pavement varied generally between 15 and 20 feet and averaged approximately 15 feet. There had been little cracking in the new part of the pavement up to the time of the survey, probably because of the use of joints at approximately 25-foot intervals.

The new part of the pavement is in good condition in every respect. In contrast, the joints and cracks in certain parts of the old pavement are badly spalled and distintegrated.

Project 50-A.—This is a four-lane pavement. The two inside lanes were built in 1923 and the two outside lanes were added in 1933. The old pavement is reinforced throughout with a special reinforcement, as indicated in tables 1 and 2. The newer pavement is reinforced throughout with a 60-pound welded fabric. The slab length of the older pavement varied generally between 14 and 20 feet and averaged approximately 17 feet. The slab length of the newer pavement varied generally between 25 and 80 feet and averaged approximately 37 feet. The newer part of the pavement was apparently in much better condition than the old pavement had been at the same age, possibly because of differences in the design and manner of placing the reinforcement in the two pavements.

Spalling had occurred at the joints and cracks in the old pavement and on one short section a considerable amount of scaling in the vicinity of the cracks was noted. The joints and cracks in the new pavement were in good condition.

Project 70-D.—The section included in this survey was originally a two-lane pavement built in 1925 to which a third lane was added in 1932.

The slab length of the older pavement varied generally between 12 and 20 feet and averaged approximately 16 feet. The slab length of the newer pavement varied generally between 20 and 75 feet and there were a number of slabs which exceeded 80 feet in length. The average slab length of the newer pavement over the entire section surveyed was approximately 38 feet at the time of the survey.

The general condition of much of the old pavement was poor, with spalling and scaling prevalent along the joints and cracks. The joints and cracks in the new part of the pavement were in good condition.

Project 131-C.—The section surveyed is a two-lane pavement built in 1930. The slab length in the first mile varied generally between 25 and 50 feet and averaged approximately 33 feet. The slab lengths in

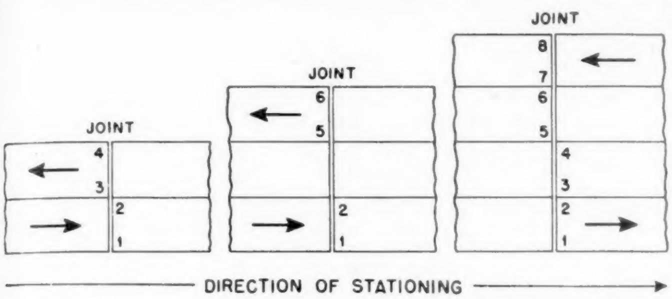

FIGURE 5.—POINTS AT WHICH FAULTING MEASUREMENTS WERE MADE ON TWO-, THREE-, AND FOUR-LANE PAVEMENTS.

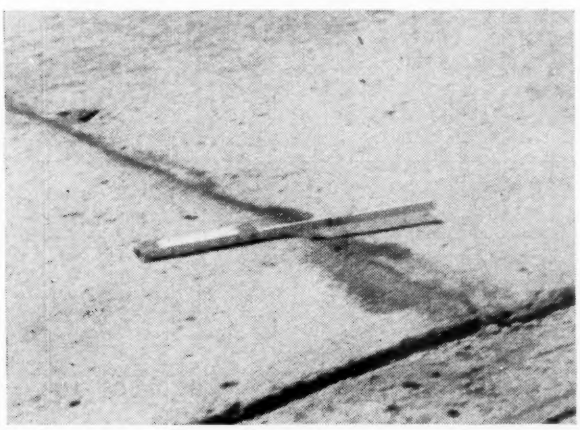

FIGURE 6.—EXPANSION JOINT FAULTED APPROXIMATELY 1 INCH WITH THE SLAB BEYOND THE JOINT DOWN.

the second and third miles varied generally from 15 to 30 feet and averaged approximately 21 feet. The greater slab length in the first mile was probably due to the more favorable subgrade conditions. The cracks and joints in this pavement were in good condition.

Project 97–A.—This is a four-lane pavement, the two center lanes of which were built in 1924 and two outside lanes were added in 1928. A great deal of cracking had occurred in this pavement which is surprising in view of the favorable subgrade conditions. The average slab length for that part of the pavement built in 1924 was approximately 17 feet, while that for the newer pavement built in 1928 was approximately 20 feet.

The concrete in the vicinity of the joints was in most cases in fairly good condition although there was spalling and scaling in the vicinity of many of the cracks in the older part of the pavement. The cracks in the newer part of the pavement were in better condition.

Project 41–R.—This is a four-lane reinforced pavement which was 7 years old at the time of the survey. The pavement was in good condition. The slab length varied generally between 20 and 30 feet although there were a number of sections where it exceeded 30 feet. The average slab length of the entire portion of the pavement surveyed was approximately 25 feet. The cracks were closed and both the joints and cracks were in good condition.

Project 150–D.—The section surveyed consisted of two 10-foot lanes constructed, one on each side of an old 20-foot pavement, which has been resurfaced. The new part of the pavement was reinforced. It was 6 years old at the time of the survey, and was in good condition. There were many long slabs, the average slab length exceeding 40 feet. The cracks were closed and both the joints and the cracks were in excellent condition.

Project 146–B.—The section studied is a two-lane pavement which was 13 years old at the time of the study. The slab length varied generally between 10 and 20 feet, the average slab length being approximately 17 feet. Some of the shorter slabs are located in areas where fills have settled or where frost action had broken the pavement. The cracks were open and a moderate amount of spalling had developed at both the joints and the cracks. The surface of the pavement may be described as being in fairly good condition.

Project 187–E.—The section surveyed is a 16-foot pavement built in 1918 and originally identified as State Reward Project No. 6269. The cross section is 6–8–6 inches and there was no longitudinal joint although a longitudinal crack has developed throughout most of the pavement.

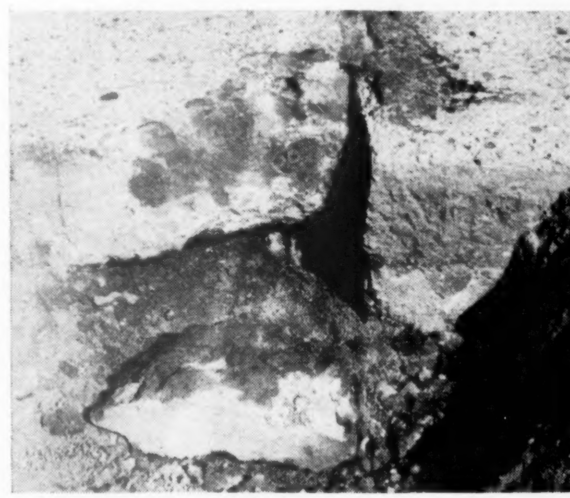

FIGURE 7.—SMALL COMPRESSION CORNER FAILURE AT A CLOSED EXPANSION JOINT.

This pavement was in good condition for its age. The average slab length was approximately 30 feet. The relatively small amount of transverse cracking that has developed may be attributed to the favorable subgrade. The dense shade which exists along most of the section may have had some influence in limiting cracking.

The joints were generally in good condition. Many of the cracks, however, were open and considerable spalling had occurred.

Certain defects were observed quite generally in all sections studied but to avoid repetition they were not mentioned in the preceding discussion. These were: (1) Faulting at joints and cracks; (2) closure of the expansion joints and the presence of foreign material in the joints and cracks; and (3) breakage and disintegration of the concrete in the vicinity of joints and cracks.

FAULTING AT JOINTS AND CRACKS

Typical data showing the magnitude and direction of faulting at a number of the joints on a two-lane pavement are shown in figure 4. The points at which faulting was measured on two-, three-, and four-lane pavements and the numbers identifying the points are shown in figure 5. Figure 4 indicates the vertical position at the different points on the slab beyond the

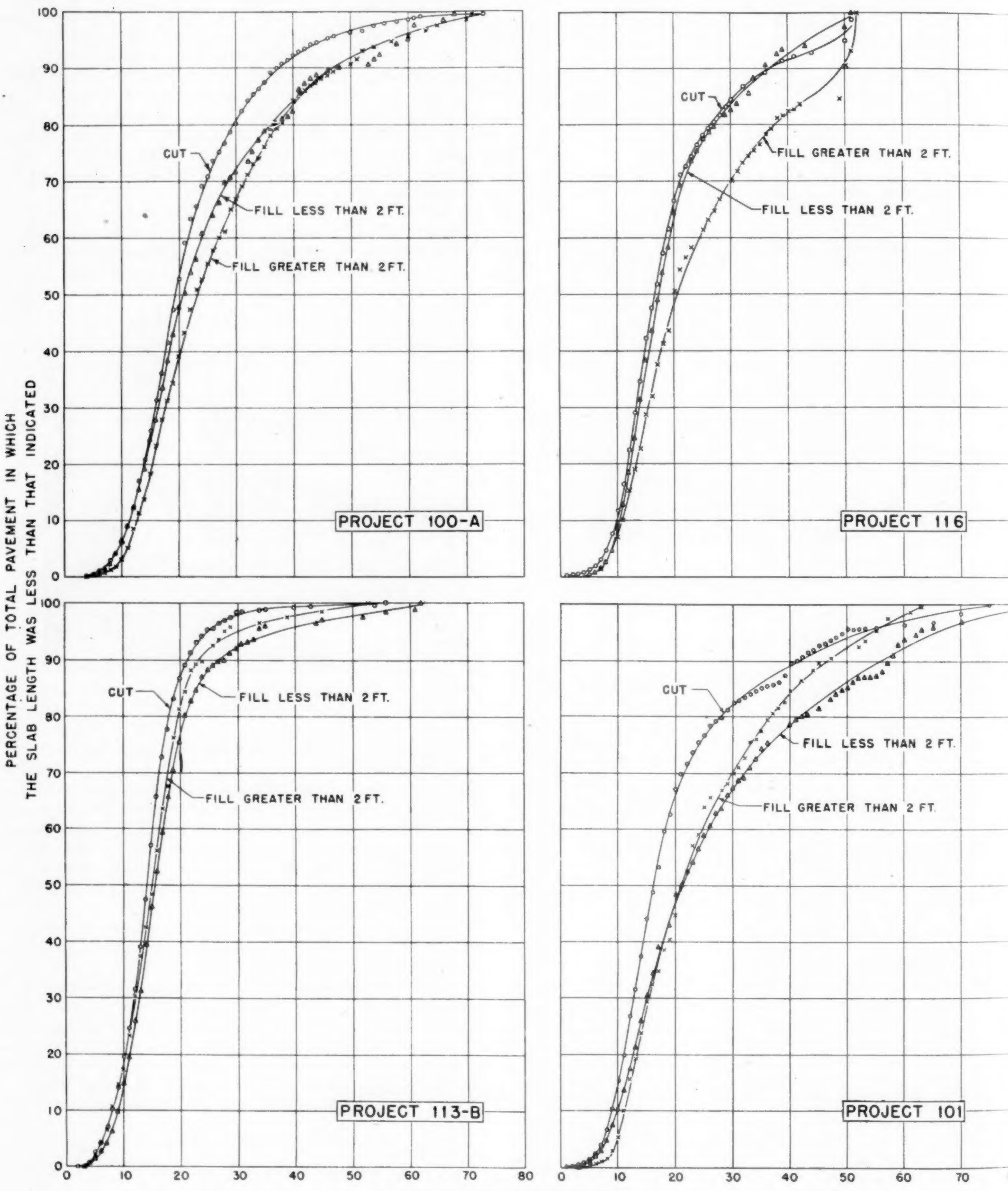

FIGURE 8.—PERCENTAGE DISTRIBUTION OF SLAB LENGTHS IN CUTS AND ON FILLS ON FOUR PROJECTS.

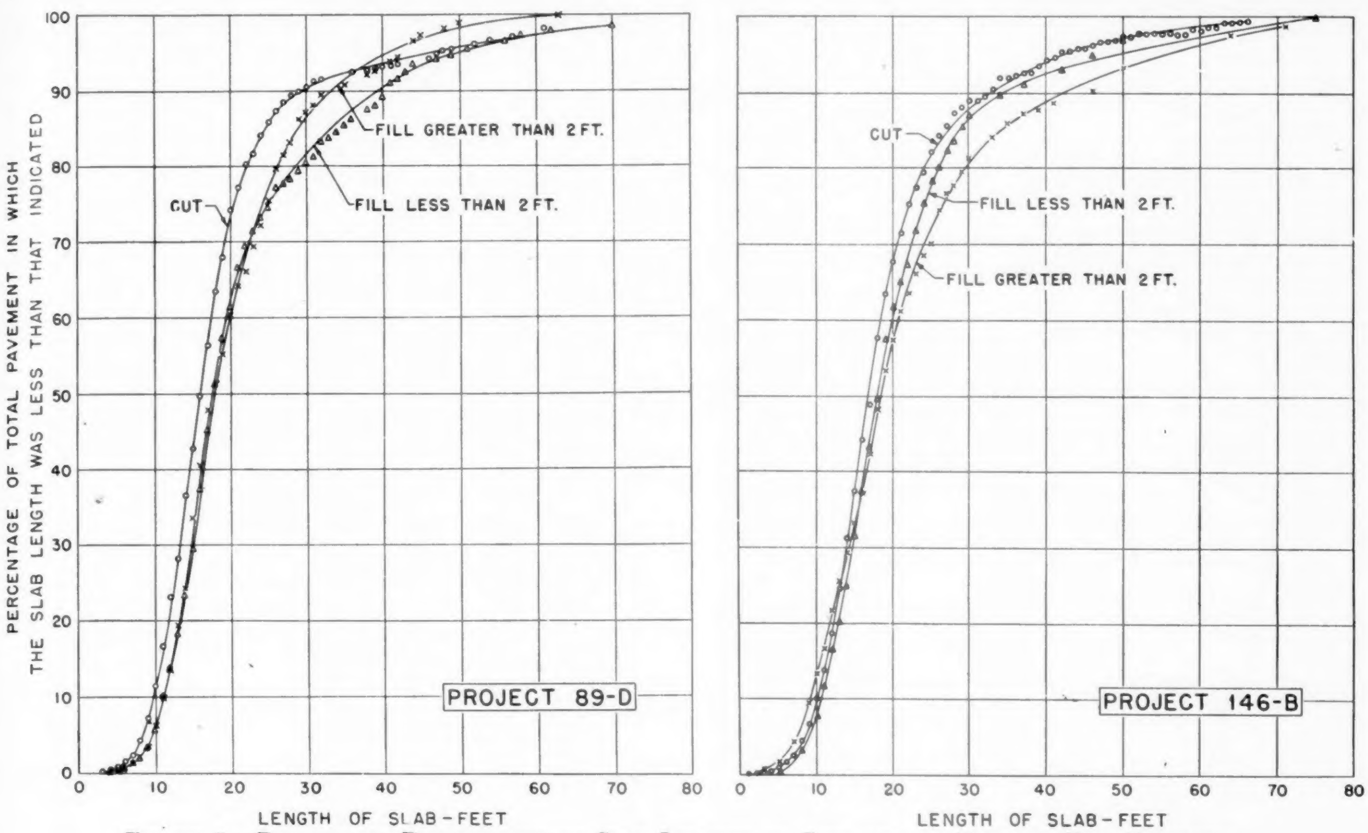

FIGURE 9.—PERCENTAGE DISTRIBUTION OF SLAB LENGTHS IN CUTS AND ON FILLS ON TWO PROJECTS.

joint with respect to the approach slab. Thus, a minus value at a given point indicates that, at this point, the slab beyond the expansion joint is below the approach slab. A positive value indicates the opposite condition.

A majority of the joints on this project were faulted. The magnitude of the faulting was generally greater at the free edges of the pavement than along the connected longitudinal joints, but at certain places a considerable degree of faulting was present near the longitudinal joint.

There appears to be no uniformity in the direction or manner of the faulting. In many cases the slab beyond the joint was below the approach slab at the free edges of the pavement, while in others the opposite condition was found. The same was true of the two points adjacent to the longitudinal joint. As a general rule, however, the slab beyond the joint was below the approach slab where the faulting was severe, that is, where the relative displacement was one-half inch or more. Such a joint is illustrated in figure 6.

While some faulting was present at cracks, the displacement was much less than at expansion joints.

On all projects the degree of faulting at the expansion joints varied with the age of the pavement, the type of subgrade, etc., but the general pattern was approximately the same. The degree of displacement found at the joints will be discussed later in connection with table 5.

CONDITION OF JOINTS AND CRACKS

A large percentage of the expansion joints examined were found to be closed or partly closed. Whatever spaces remained between the slab ends were filled with hard, compressed soil. This condition had brought about a number of small compression corner failures of the type shown in figure 7. In many of the sections a large percentage of the transverse cracks were open and badly spalled and disintegrated.

A summary of the pertinent facts found in the study s given in table 5.

AVERAGE SLAB LENGTH OF CONCRETE PAVEMENTS DETERMINED FOR VARIOUS SUBGRADE AND TRAFFIC CONDITIONS

The data were examined to determine the effect of a number of variables on the average slab lengths of the various pavements as shown in table 5.

The effect of cut and fill on average slab length.—This relation is shown in figures 8 and 9, inclusive. These are typical distribution curves in which the abscissas indicate slab lengths while the corresponding ordinates represent the percentage of the total pavement length formed by slabs of that length or less.

The depth of fill used in the construction of these graphs is the average for the two sides of the pavement. While the depths of the fill at the edges of the pavement generally refer to the natural ground, they sometimes differ considerably from the actual depth of fill placed at the center of the pavement at the last construction, since a number of the pavements were built over old roadbeds and the depths of the fills were measured to the old roadbeds. The depths of the fills on the sides of the pavement were not, as a rule, influenced by the old road because the new surface was generally built wider than the existing road.

In interpreting the graphs, it should be emphasized that there are relatively few long slabs in many of the pavements from which the data were obtained. Thus the upper parts of these curves represent only small samples of pavements. Also, on some of the projects the total length of pavement, on fills greater than 2 feet in height, was relatively small. These facts may ex-

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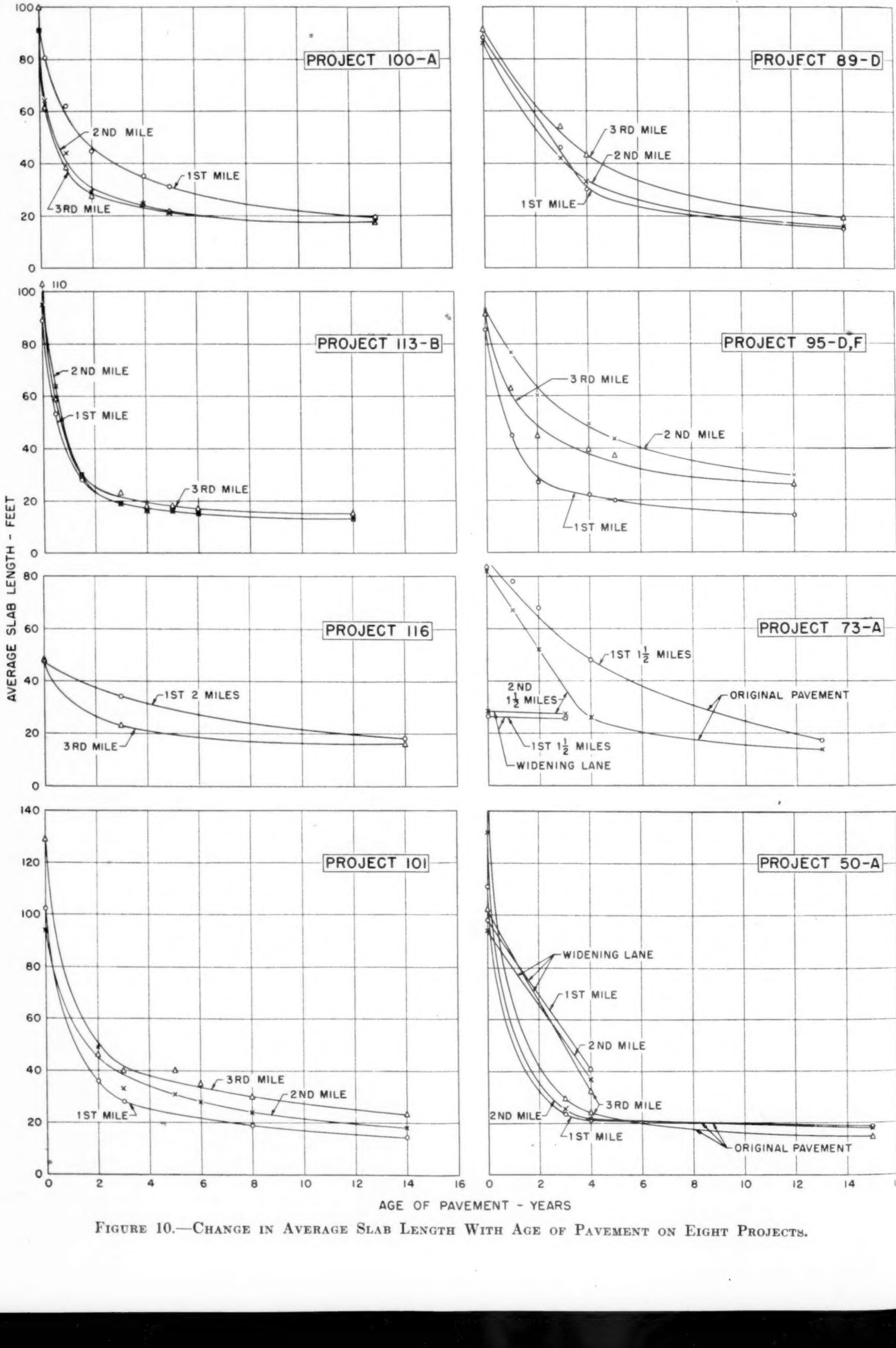

Figure 10.—Change in Average Slab Length With Age of Pavement on Eight Projects.

plain certain inconsistencies in some of these graphs, especially in the upper ends of the curves.

The graphs are consistent in showing a greater slab length on fills than in cuts. The difference is not great for that half of the pavement lengths having the shortest slabs, but is of some size where slabs were longest. In some cases the slab lengths are greater on fills less than 2 feet in depth than on fills more than 2 feet in depth, while in other cases the opposite is true. The subgrade material on projects 100–A and 113–B is clay, while that on projects 116 and 101 is predominantly sandy. The subgrade material on projects 89–D and 146–B is variable.

In the cuts the percentage of pavement with an average slab length of 20 feet or greater is approximately the same for the three types of subgrade material. On the fills however the percentage is somewhat greater for pavement on sandy subgrade.

AVERAGE SLAB LENGTH OF CONCRETE PAVEMENTS AT DIFFERENT AGES

The average slab lengths at different ages for certain sections examined for which data from former crack surveys were available are shown in figures 10 and 11. On some of the newer pavements only one crack survey had been made and for these only the original slab lengths and slab lengths at the time of this survey can be shown.

The more recently built pavements (projects 73–A, 50–A, 70–D, and 146–B) shown in figures 10 and 11 are separate lanes 10 feet in width which have been placed along the side of older pavements. These lanes generally were laid on the same types of subgrades as the old pavements. Reinforcement has been incorporated more generally in the newer pavements than in the older ones and the effect of this reinforcement will be discussed later in the report.

Figures listed above consistently show that, for these pavements, transverse cracking greatly reduces the average slab length and the greatest reduction in slab length occurs within the first few years of life of the pavement. The majority of the transverse cracks developed during the first 4 years on these projects. All of the pavements tend to reach an ultimate average slab length between 15 and 20 feet.

The average slab lengths of the widening lanes on projects 50–A and 70–D are greater than those of the original pavement at the same age. The average slab length of the newer pavement on project 97–A is practically the same as that of the old pavement at the same age.

The average slab length of the new pavement on project 73–A is much less than that of the old pavement at the same age, for the reason that joints were placed at intervals of approximately 25 feet in the new pavement at the time it was built. Figure 10 (project 73–A) shows that very little cracking occurred during the first 3 years of the life of the new pavement, a condition that is undoubtedly due to the fact that the pavement was originally constructed in 25-foot slabs.

AVERAGE SLAB LENGTHS OF PAVEMENTS ON DIFFERENT SUBGRADE MATERIALS COMPARED

In figure 12 the average slab length for the separate miles within each section are shown grouped according to the general type of the subgrade material on which the pavement was laid. There are two general types of material represented, the clays, falling generally in the A–6 group and the sandy soils of the A–3 group.

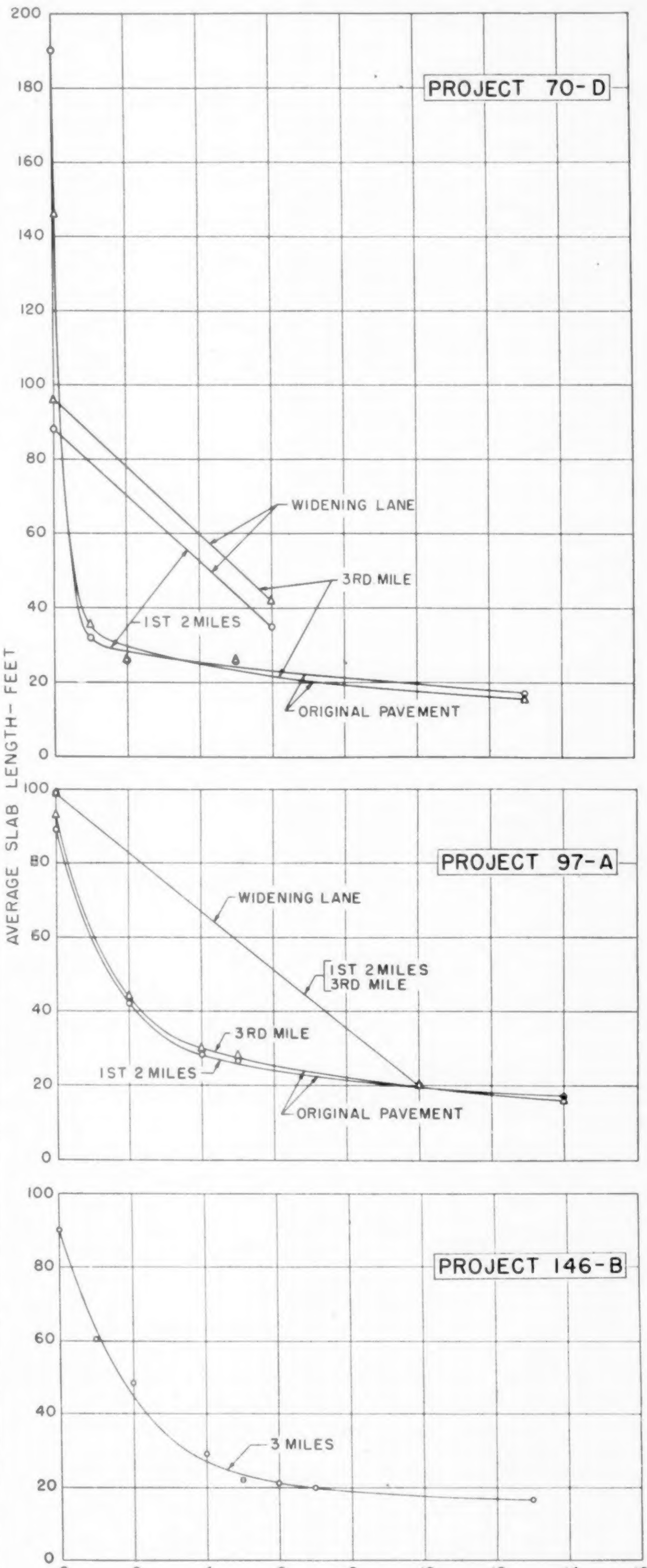

FIGURE 11.—CHANGE IN AVERAGE SLAB LENGTH WITH AGE OF PAVEMENT ON THREE PROJECTS.

In some cases the clay materials approach the A–7 group and the soil of one project (187–E) was classed as A–1, approaching A–3. In general, the sandy

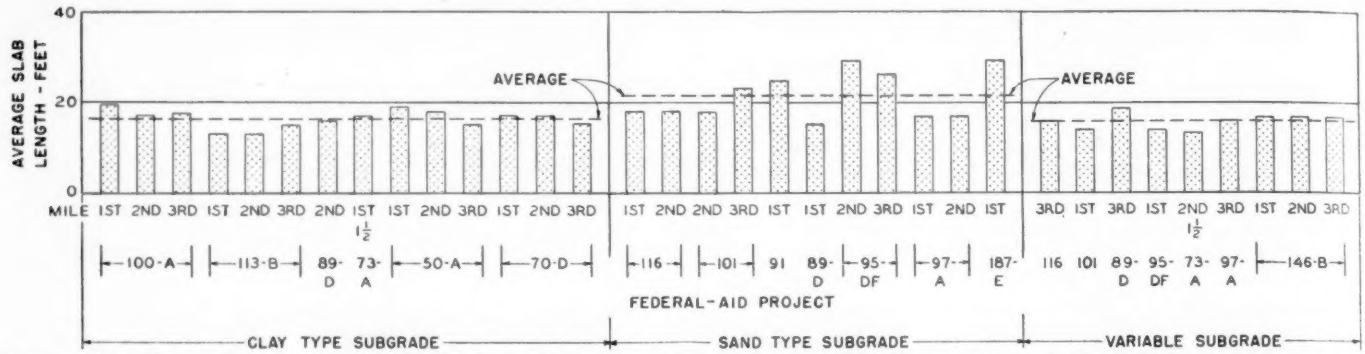

FIGURE 12.—COMPARISON OF THE AVERAGE SLAB LENGTHS OF PAVEMENTS ON DIFFERENT TYPES OF SUBGRADES. THESE PAVEMENTS RANGE IN AGE FROM 12 TO 15 YEARS, WITH THE EXCEPTION OF 187–E WHICH IS 20 YEARS OLD.

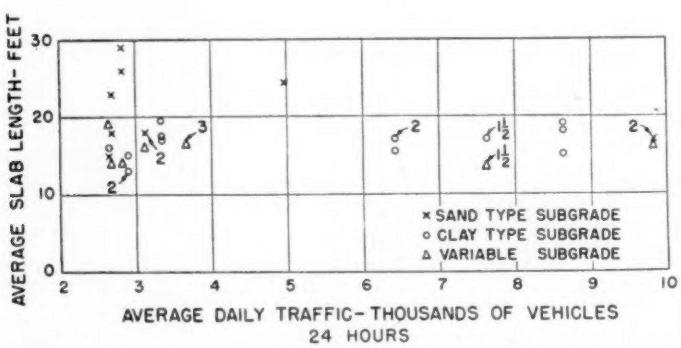

FIGURE 13.—COMPARISON OF AVERAGE SLAB LENGTHS ON PAVEMENTS WITH DIFFERENT AMOUNTS OF TRAFFIC. EACH POINT REPRESENTS 1 MILE EXCEPT WHERE INDICATED DIFFERENTLY. PAVEMENTS RANGE IN AGE FROM 12 TO 15 YEARS.

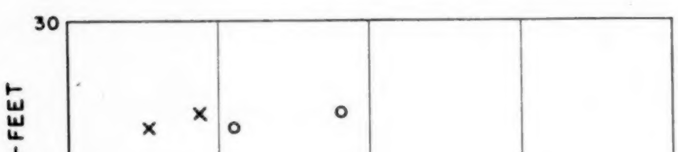

FIGURE 14.—COMPARISON OF AVERAGE SLAB LENGTHS ON PAVEMENTS HAVING DIFFERENT AMOUNTS OF HEAVY TRUCK TRAFFIC. EACH POINT REPRESENTS A SECTION OF PAVEMENT OF ABOUT 3 MILES. PAVEMENTS RANGE IN AGE FROM 12 TO 15 YEARS.

materials are considered to be better than the clays. The subgrade materials that are classified as variable are of the same general character as the clay or sandy subgrades but change from one type to the other, one or more times within the mile of pavement surveyed. No tests were made to determine the density and the moisture state of the subgrades under the various pavements studied. The very general nature of the survey and the considerable mileage of pavement involved made it impracticable to include such tests.

All of the pavements included in this comparison were between 12 and 15 years old, except that on project 187–E which was 20 years old.

Figure 12 shows an average slab length of approximately 16 feet on both the clay and the variable type subgrades, while that on the sandy material was approximately 21 feet. Thus the average slab length on the sandy soils was approximately 30 percent greater than that on the clay soils. It is noted that the average slab length for project 187–E was greater than that on any other project. This was probably the result of favorable subgrade conditions and the removal of some of the poorest sections of the pavement before the survey was made.

Sand and gravel subbases were placed on certain parts of projects 113–B, 116, 101, and 73–A (see table 4). It was found that the average slab length for the parts of the pavement laid over these subbases was approximately the same as those for other parts of the pavement. It may be assumed that these subbases were placed to correct some defect in the subgrade at the time the pavements were built and it appears that, in general, the pavements where the subbase was used were as satisfactory as those on the remainder of the subgrade.

Parts of some of the pavements in figure 12 had small amounts of special reinforcement. This reinforcement had not influenced the average slab length of the pavements sufficiently to affect the relations shown. The effect of reinforcement in general is discussed later in the report.

TRAFFIC VOLUME HAD NO IMPORTANT EFFECT ON SLAB LENGTH

Figures 13 and 14 show the relation between the average slab lengths of the various pavements and the amount of traffic they carry. The slab length and traffic data from which these graphs were constructed are shown in table 5. These traffic data were collected during 1936 after most of the cracking in the pavements had already occurred. Also a few of the surfaces were widened to three and four lanes some time after they were built and this has had an important effect on the traffic in a given pavement lane. Figure 13 indicates that there were a greater number of the longer slabs on the pavements with light traffic however, the longer average slab lengths were for pavements laid on the sandy subgrades.

Considering the data as a whole, it must be concluded from figure 13 that, so far as these surfaces are

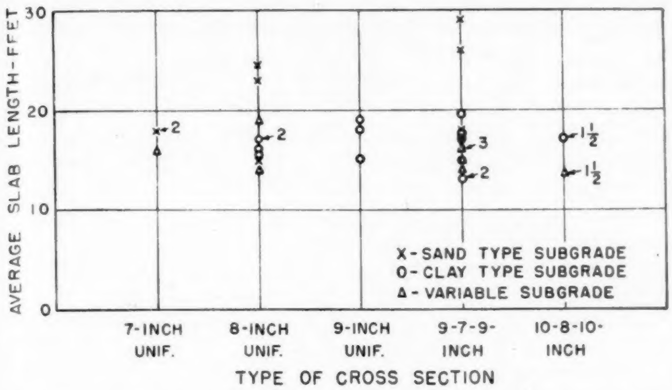

Figure 15.—Comparison of Average Slab Lengths With Different Types of Cross Sections. Each Point Represents 1 Mile Except Where Indicated Differently. Pavements Range in Age From 12 to 15 Years.

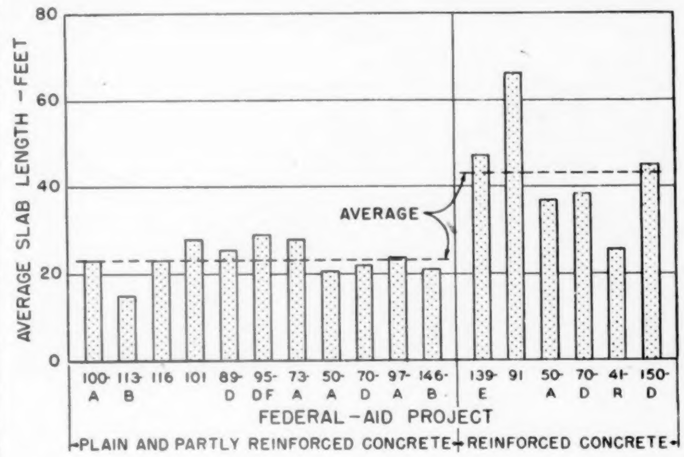

Figure 16.—Comparison of the Average Slab Lengths on Plain and Reinforced Concrete Pavements. The Reinforced Pavements Vary in Age From 5 to 7 Years and Have an Average Age of 6.3 Years. The Average Slab Lengths of the Plain Concrete Pavements Were Taken at a Corresponding Age. The Reinforced Pavements Were Reinforced With a 60-Pound Wire Fabric.

concerned, the average daily traffic has had no important effect on the average slab length.

In figure 14 the average slab lengths are plotted against the daily number of wheel loads of different weight classes. Neither the number of wheel loads of a magnitude of 4,000 pounds or greater, nor the number of a magnitude of 6,000 pounds or greater appears to have had any important influence on the amount of transverse cracking that had occurred. Table 5 shows that there were very few wheel loads exceeding 9,000 pounds on these pavements.

While the traffic data used were obtained in surveys made after most of the transverse cracking had taken place, it is thought that the figures do give an indication of the relative amount of traffic that has been moving over the various sections during the earlier life of the pavement.

CROSS SECTION DID NOT INFLUENCE SLAB LENGTH

A study of the relation between the average slab length and the design of cross section is summarized in figure 15. The types of subgrade on which these pavements were laid are indicated by symbols.

To draw definite conclusions from data of the kind presented in figure 15, it is necessary that all other factors are constant throughout. This obviously is not the case. The comparison has other weaknesses. Only the 8-inch uniform thickness and the 9–7–9 inch thickened-edge pavements are represented by a sufficient number of miles to make the values dependable. Also the range of types is not as wide as is desirable. It can only be concluded that the data presented indicate that the shape and thickness of the pavement cross section has little or no influence on the average slab length.

AVERAGE SLAB LENGTHS OF PLAIN AND REINFORCED PAVEMENTS COMPARED

A comparison is made between the average slab lengths of plain and reinforced pavements in figure 16. The reinforced pavements available for this comparison ranged in age from 5 to 7 years and had an average age of 6⅓ years. The average slab lengths of the plain concrete pavements were taken from figures 10 to 11 at the corresponding age of 6⅓ years.

The first group of pavements in figure 16 are plain and partly reinforced. The majority of these pavements had ¾-inch diameter edge bars and projects 100–A, 101, 50–A, and 70–D had small amounts of special reinforcing in certain areas. The details of the special reinforcement are given in tables 1 and 2. A study of the parts of the pavements with special reinforcement indicated that it had no appreciable effect on the structural properties or condition of the pavement. This was probably due to the small amounts of reinforcement used or to the manner in which it was placed.

Project 50–A is the only one in which special reinforcement was placed in a large part of the total length of the pavement. The average slab length on this project was only slightly greater than the average for all the pavements on a similar type of subgrade.

None of the pavements containing special reinforcement, mentioned above, was reinforced with wire fabric. Each of the pavements included in the second group of figure 16 was reinforced throughout with a 60-pound fabric. The percentages of clay and sandy types of subgrades were approximately equal under both the plain and the reinforced pavements. Thus the effect of the type of subgrade may be disregarded in the interpretation of this figure. In some cases the reinforced pavements were single lanes placed along the edges of the old pavement.

It is apparent from figure 16 that the average slab lengths for the pavements containing distributed reinforcement were much greater than were those of the plain concrete pavements at the same age. The average slab length for all the reinforced pavements was more than 80 percent greater than the average for all the plain concrete pavements.

Two projects (50–A and 70–D), represented in this figure, had both plain and reinforced pavements. The type of subgrade under the plain and reinforced pavements on the two sections was the same, yet the average slab lengths for the reinforced pavement greatly exceeded those for the plain pavements.

A 60-pound welded wire fabric, such as was used in the reinforced pavements, is relatively light reinforce-

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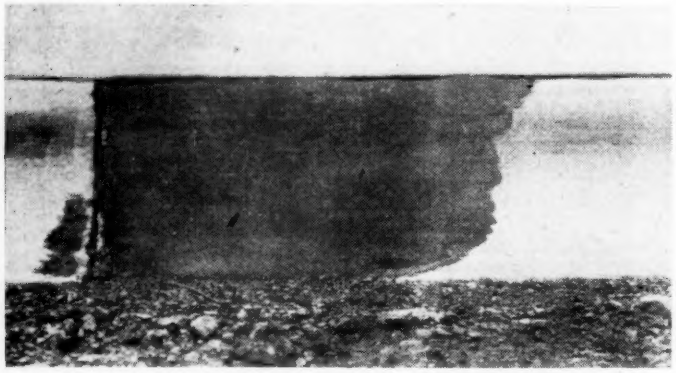

FIGURE 17.—BADLY FAULTED JOINT WITH LEADING SLAB DEPRESSED.

ment for heavy pavement sections. This weight of reinforcement is ordinarily associated with design slab lengths of 50 feet or less. On all but one of these six projects it was used with a constructed slab length of about 100 feet. While it is possible that cracks were present and were held so tightly closed by the reinforcement that they passed undetected, it is believed that such cracks were not numerous.

It is generally conceded that small amounts of reinforcement placed near the neutral axis of a concrete pavement have little or no influence in preventing cracking from wheel loads. The greatest part of the cracking in these pavements apparently had been caused by combined load and warping stresses, and it is possible that where warping stresses are involved small amounts of reinforcement may act in some manner to delay or reduce cracking. Regardless of whether or not this is the explanation, it is indicated that over the present life of these pavements the reinforcement has had the practical effect of increasing appreciably the average slab length and that this effect is likely to continue.

There is another factor that should not be overlooked, however, even though it may not be possible to evaluate its influence. Important changes have taken place in the character of traffic, particularly in that fraction which includes the heavier wheel loads, during the past 10 or 15 years. Speeds have increased greatly and the type of tire equipment has changed radically. For a given wheel load, the strains produced in the pavement slab are probably less now than they were 15 years ago and pavements laid at that time may have been damaged more by heavy wheel loads than were similar pavements placed at a later date. The matter is complex and is only mentioned here to record the fact that this trend exists and is recognized.

ONLY SMALL NUMBER OF CORNER CRACKS FOUND

Corner breaks.—The corner breaks recorded in table 5 are those that were found at expansion joints. The majority of these breaks were located during earlier surveys and are no longer visible because of repairs. At the time of the present survey practically no corner breaks were visible and those that were found were usually at inside corners, next to the longitudinal joints and much smaller than the cracks resulting from load failure sometimes found at outside corners.

Table 5 shows that the number of breaks occurring in the pavements surveyed was very small. Several factors are believed to have contributed to this condition. The concrete pavements, with two exceptions, had edge thicknesses of 8 to 10 inches. The cross sections were of 9–7–9 or 10–8–10 inch thickened-edge design or of 8-, 9-, or 10-inch uniform thickness. Thus, the exterior corners of most of the pavements were relatively heavy. Wide pavements and high operating speeds tend to remove the point of load applications from the extreme edge of the pavement, while better cushioning in the tire equipment tends further to protect slab corners by reducing the impact forces developed at transverse joints.

Discussion of faulting at joints.—Faulting at joints was discussed in a general way for the individual projects in connection with figure 4. The summary of the faulting conditions at joints given in table 5 shows the percentage of joints per lane at which each of three different degrees of vertical displacement were found, the differences indicated in this table being based on the maximum faulting found by measurement in either direction and at any point across the width of the one lane.

It will be noted from these data that on 5 of the older and on 1 of the newer pavements 40 percent or more of the joints had faulted one-fourth inch or more at some point along the joint. The term "newer pavements" includes those built since 1930. On 10 of the older pavements and on 5 of the newer, this same proportion of joints, 40 percent or more, had faulted one-eighth or three-sixteenth inch. Only 1 of the new pavements, project 73–A, had one-sixteenth-inch faults at 40 percent or more of the joints. On 11 of the older pavements and 3 of the newer pavements, 25 percent or more of the joints had faults of one-fourth of an inch or greater. This same proportion of joints (25 percent or more) had faulted one-eighth or three-sixteenth inch on 14 of the older pavements and on 6 of the newer. Only 4 of the pavements had 25 percent or more of the joints with faults of one-sixteenth inch. Two of these were old pavements and 2 were new.

Generally speaking, the most undesirable conditions of faulting were on those projects with the highest percentage of joints that had faulted one-fourth of an inch or more.

Faulting measurements of less than one-eighth inch approach the limit of accuracy of the method used. For this reason some of the joints recorded as having differences of elevation of less than one-eighth inch may not actually be faulted. Because of the large number of measurements made, however, the tendency would be for these errors to cancel out.

It is interesting to compare the condition of the joints in the older and newer sections of projects 73–A and 50–A. On both projects the subgrade material is of the same type over a large part of the length. On project 73–A, a 6- to 10-inch sand and gravel subbase underlies a considerable part of the old pavement and at the time of the survey was in a dry, well-drained condition. The old pavements on both sections were of approximately the same age and had been subjected to approximately the same amount of traffic.

While there was an undesirable amount of faulting in both pavements, the number of badly faulted joints was less on project 73–A than on 50–A, and comparison indicates that the sand and gravel subbase had been of some benefit in reducing faulting at the joints.

The newer pavement of project 73–A was 3 years old at the time of the survey, and that of project 50–A was 5 years old. Provision for load transfer had been in-

cluded in project 73–A, while no load-transfer devices were used in project 50–A. Very little faulting had occurred at the joints of the new pavement in project 73–A, while the faulting at the joints of the new pavement on project 50–A was worse than that of almost any other project studied. For example, table 5 shows that only 2 percent of the joints in the new pavement of project 73–A were faulted one-fourth of an inch or more, while 48 percent of the joints in the new pavement of project 50–A were displaced this amount. This comparison shows very clearly the beneficial action of adequate load-transfer devices in maintaining slab surface alinement at expansion joints.

FAULTING WAS OF TWO TYPES

The data collected in this investigation indicate that there are two distinct types or phases of the phenomenon of faulting. The first type is that in which transverse cracks develop in the pavement near the joints. If the pavement is not reinforced, this crack creates a short slab supported by the subgrade but with no direct structural connection with the other parts of the pavement. The short slabs gradually become displaced vertically at the joints. The magnitude of the displacement is generally less than one-half inch and the joint may be faulted in either direction, that is the slab beyond the joint in the direction of traffic may be either above or below the approach slab and lateral tilting may accompany the displacement. This type of faulting was found to be very general on practically all of the pavements investigated and was present on all of the different types of subgrades.

In the second type of faulting, the slab beyond the joint in the direction of traffic is depressed below the approach slab and the magnitude of the displacement may be as much as one-half inch and frequently exceeds this amount.

A typical example of this type of faulting is shown in figure 17. When such a depression develops, it is frequently necessary to level up the surface with bituminous material for a short distance on the depressed slab.

Table 6 shows the percentage of joints on each project at which a displacement of one-half inch or more had developed. The different miles surveyed in the various projects are separated according to the type of subgrade to indicate the influence of the subgrade on this type of faulting. In the fifth column of this table the percentage of joints at which the slab beyond the joint is depressed is shown, while the sixth column gives the percentage of joints at which the approach slab is depressed. A joint was recorded as faulted one-half inch or more if displacements of this magnitude were measured at any point along the joint. The length of a joint was considered as being the width of one lane.

The table shows only one pavement in which an appreciable number of the joints have the approach slab depressed one-half inch or more. It appears to be a general characteristic that where severe faulting develops at a joint, the slab beyond the joint is depressed with respect to the approach slab.

Table 6 presents data on 120 lane-miles of highway. Of this amount 48.5 lane-miles were on a clay type subgrade, 36 lane-miles were on a sand type subgrade, and 35.5 lane-miles were on variable subgrade. The clay type subgrades were generally A–6 soils and the sand type subgrades were generally A–3 soils. The variable subgrades generally included both the clay and sand types, changing within the mile surveyed.

TABLE 6.—*Data on badly faulted joints*

Federal-aid project No.	Year built	Mile surveyed	General type of subgrade	Joints faulted ½ inch or more: Slab beyond joint down	Joints faulted ½ inch or more: Approach slab down
				Percent	*Percent*
100–A	1925	1, 2, 3	Clay	6	1
113–B	1926	1, 2, 3	do	8	0
116	1924	1, 2	Sand	2	1
		3	Variable	2	1
101	1924	1	do	12	1
		2, 3	Sand	5	0
139–E	1931	1, 2	do	0	0
91	1923	1	do	(1)	(1)
91	1931	1	do	0	0
89–D	1924	1	do	1	0
		2	Clay	1	0
		3	Variable	0	0
95–DF	1926	1	do	3	0
		2, 3	Sand	1	0
73–A	1925	First 1½	Clay	2	0
		Second 1½	Variable	2	0
73–A	1935	First 1½	Clay	0	0
		Second 1½	Variable	0	0
50–A	1923	1, 2, 3	Clay	9	5
50–A	1933	1, 2, 3	do	10	1
70–D	1925	1, 2, 3	do	2	0
70–D	1932	1, 2, 3	do	1	0
131–C	1930	1	Sand	0	0
		2	Clay	5	0
		3	Variable	1	2
97–A	1924	1, 2	Sand	4	0
		3	Variable	3	0
97–A	1928	1, 2	Sand	10	1
		3	Variable	6	0
41–R	1931	1, 3	do	3	0
		2	Clay	9	1
150–D	1932	First 1½	do	4	0
		Second 1½	Variable	1	0
146–B	1925	1, 2, 3	do	4	1
187–E	1918	1	Sand	3	2

[1] No joints.

Considering those projects where 8 percent or more of the joints were faulted one-half inch or more, with the slab beyond the joint depressed, it is found that 72 percent of the lane-miles were on the clay type subgrades, 18 percent were on the sand type subgrades, and 10 percent were on variable subgrades.

Considering those projects in which 5 percent or more of the joints were faulted one-half inch or more, with the slab beyond the joint depressed, it is found that 65 percent of the lane-miles were on clay type subgrades, 23 percent were on sand type subgrades, and 12 percent were on variable subgrades.

Of those pavements of table 6 that were built before 1931, 31 lane-miles were on a clay type subgrade, 26 lane-miles on a sand type subgrade, and 23 lane-miles were on variable subgrade.

In this group 8 percent or more of the joints were faulted one-half inch or more with the slab beyond the joint depressed and of this fraction 62 percent were on the clay type subgrades, 24 percent were on the sand type subgrades, and 14 percent were on variable subgrades.

It is indicated that faulting in which the slab beyond the joint is depressed one-half inch or more occurs more frequently on pavements supported by subgrades of the clay type but that it may also develop in those placed on sandy material.

This type of faulting may develop at an early age. A relatively large percentage of the joints were faulted on the new pavement of project 50–A and on the second mile of project 41–R.

TABLE 7.—*Data on cracking near joints*

Federal-aid project No.	Year built	Lane-miles of pavement	Number of expansion joints per lane-mile	Number of cracks expressed as a percentage of the number of joints within—		Percentage of joints having cracks in slab beyond the joint within—		Percentage of joints having cracks in approach slab within—	
				8 feet of joint	11 feet of joint	8 feet of joint	11 feet of joint	8 feet of joint	11 feet of joint
				Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
100-A	1925	6	56	11	27	4	12	4	14
113-B	1926	6	54	26	65	10	26	14	32
116	1924	6	106	7	21	2	11	3	12
101	1924	6	49	12	37	6	17	4	19
139-E	1931	8	58	0	2	0	0	0	0
91	1931	2	58	2	3	1	2	0	1
89D	1924	6	60	5	20	2	11	2	11
95-DF	1926	6	59	12	36	3	15	7	21
73-A	1925	6	63	22	44	15	30	6	21
	1935	3	105	1	2	0	1	1	1
50-A	1923	6	40	12	17	8	12	2	5
	1933	6	54	11	18	8	12	5	7
70-D	1925	6	30	17	27	9	18	5	12
	1932	3	58	2	3	1	3	0	1
131-C	1930	6	56	2	5	1	3	1	3
97-A	1924	6	58	16	40	7	21	7	18
	1928	6	53	9	23	8	14	2	13
41-R	1931	12	108	1	2	0	1	0	0
150-D	1932	6	63	0	2	0	0	0	0
146-B	1925	6	59	15	30	7	17	5	16
187-E	1918	2	73	5	15	6	8	1	4

FAULTING AT TRANSVERSE CRACKS

Table 5 gives data on differences in slab elevation at both joints and cracks. Faulting measurements were made at only one selected crack in approximately each 100 feet surveyed. This, generally, represented between 15 and 20 percent of the total number of transverse cracks in the pavement. The older and generally the more open cracks were selected for faulting measurements and it is estimated that they were representative of approximately 50 percent of the total number of cracks in the different pavements.

The data on faulting at cracks of table 5 are based on the number of cracks at which faulting measurements were made. These percentages refer, therefore, to the older cracks, constituting about 50 percent of the total, which were probably those at which most of the faulting had developed. It is obvious that the percentage values would be much lower if they were based on the total number of cracks.

It is indicated by the data of this table that the tendency toward faulting at transverse cracks is much less than it is at expansion joints without provision for load transfer. There was only one pavement in which cracks with faults of one-fourth inch or more exceeded 10 percent. This was project 187-E built in 1918.

It is thought that use of longitudinal joints and of edge bars have been beneficial in reducing faulting at cracks. It is believed that the greater faulting at cracks observed on State project 187-E is partly accounted for by the absence of these features.

There is too much difference in ages between the plain and the reinforced pavements to permit a direct comparison of the amount of the faulting which had developed at the cracks. On several of the reinforced pavements the cracks were closed so tightly that faulting measurements were not attempted. These projects are indicated by the absence of entries in table 5. On some of the reinforced pavements a small number of cracks were open slightly and at some of these a certain amount of faulting had occurred.

With few exceptions, on all of the reinforced pavements examined, the slab surfaces adjacent to transverse cracks were in good alinement and in good general condition.

SIGNIFICANCE OF TRANSVERSE CRACKS NEAR EXPANSION JOINTS DISCUSSED

In the course of study of the effect on pavement condition of the omission load-transfer devices at expansion joints, it was noted frequently that transverse cracks had formed in rather close proximity to expansion joints. Table 5 shows the number of such cracks found in the sections surveyed, arbitrarily grouped within zones having a width of 8 feet or 11 feet on either side of the transverse joint.

Table 7 presents the data in a somewhat different manner. The number of cracks is related to the number of joints and also the cracks are divided into those appearing in the approach slab as compared with those in the slab beyond the joint. In each case the number is expressed as a percentage of the number of joints.

Table 7 shows that on five projects the number of cracks within 8 feet of the joints was 15 percent or more of the number of joints. These are projects 113-B, 73-A, 70-D, 97-A, and 146-B. Three of these projects had subgrades that were predominantly clay, one had a subgrade that was predominantly of a sand type, while the subgrade on the fifth was variable.

On six projects the number of cracks within 11 feet of the joints exceeded 30 percent of the number of joints. These are projects 113-B, 101, 95-DF, 73-A, and 146-B. Two of these projects had subgrades that were predominantly clay, three had subgrades that were predominantly sand, while the sixth had a variable subgrade material.

A study of the table shows that there was no consistent difference between the number of cracks near the joints in the slab beyond the joint and the number in the approach slab. The average number of cracks for all pavements having cracks in the slab beyond the joint within 8 feet of the joint was 4 percent of the number of joints, while the corresponding number with cracks in the approach slab was 3 percent. The average number of cracks for all of the pavements having cracks in the slab beyond the joint within 11 feet of the joint was 10 percent, while the corresponding number having cracks in the approach slab was 10 percent.

In the discussion of faulting at joints two types were described. The more serious type was that in which the slab beyond the joint in the direction of traffic was depressed one-half inch or more below the approach slab. The percentage of joints at which this type of faulting had taken place is indicated in table 6 and has already been discussed.

It is desirable to reexamine the data to determine whether there is evidence that impact produced by heavy wheel loads passing over the faulted joints caused transverse cracks to occur beyond the joint.

As stated previously, there are indications, at some of the joints examined, that the faults existing at the time of the survey developed after a transverse crack formed near the joint or that the magnitude of the displacement changed considerably after the formation of a crack. If this were true, a direct comparison of the number of cracks near joints in the slab beyond the joint that are now badly faulted with the number of cracks near joints that are not would not necessarily give a reliable indication of the effect of vehicle impact. A different approach is necessary.

Only those pavements built before 1927 were considered and these were divided into two groups on the basis of the number of badly faulted joints found.

TABLE 8.—*Longitudinal cracking*

Federal-aid project No.	Longitudinal cracking at distances greater than 2 feet from edge of pavement
	Lineal feet per lane-mile
100–A	64
113–B	68
116	160
101	194
139–E	5
91, old	103
91, new	4
89–D	4
95–D	174
73–A, old	85
73–A, new	0
50–A, old	13
50–A, new	2
70–D, old	41
70–D, new	0
131–C	15
97–A, old	79
97–A, new	61
41–R	0
150–D, new	0
146–B	144
187–E	(1)

[1] Practically the entire length.

The conditions of cracking in the vicinity of the joints in one group were then compared with the conditions existing on the other.

The first group includes projects 100–A, 113–B, 101, and 50–A (old section). These were selected from table 6 as having the greatest number of badly faulted joints since at 5 percent or more of the joints the slab beyond the joint was depressed one-half inch or more. Projects 116, 89–D, 95–DF, 73–A (old section), and 70–D (old section) were selected as having the smallest number of badly faulted joints. At only 2 percent or less of the joints on these projects was the slab beyond the joint depressed one-half inch or more.

For a comparison to be valid, it is necessary to assume that the relation between the two groups as to faulting at the joints had not changed appreciably for some time. This is believed to be a reasonable assumption, since in general the pavements that had a large number of badly faulted joints were those on subgrades which are conducive to this condition, while those that had relatively few badly faulted joints were those on more stable subgrades.

In the group of pavements with the larger percentage of badly faulted joints an average of 7 percent of the slabs beyond the joints had cracks within 8 feet of the joints as compared to 6 percent in the approach slabs. In this same group of pavements, 17 percent of the joints were associated with cracks in the slab beyond the joint within 11 feet of the joint as compared to 18 percent for the approach slabs.

In the group of projects with the smaller percentage of badly faulted joints, an average of 6 percent of the joints were associated with cracks in the slab beyond the joint within 8 feet of the joints as compared to 4 percent for the approach slabs. In this group 16 percent of the slabs beyond the joints had cracks within 11 feet of the joints compared to 15 percent of the approach slabs.

ONLY LIMITED AMOUNT OF LONGITUDINAL CRACKING FOUND

Considering only the slabs beyond the joints it was found for the first group of pavements, 7 percent of the slabs had cracks within 8 feet of the joints, while in the second group 6 percent of the slabs had cracks within 8 feet of the joints. Seventeen percent of the slabs in the first group had cracks within 11 feet of the joints, as compared to 16 percent in the second group.

This comparison indicates that regardless of the severity of the faulting, there was as great a tendency for cracks to form in the approach slab as there was in the slab beyond the joint and further that there was as great a percentage of cracks near the joints in the group of pavements that had the fewest badly faulted joints as there was in the group that had the most badly faulted joints.

TABLE 9.—*General condition of expansion joints* [1]

Federal-aid project No.	Year built	Original joint opening	Average joint spacing	Reinforcement [2]	Present joint openings: Closed, open ⅛ inch or less	Present joint openings: Open ⅛ to ¼ inch	Present joint openings: Open ⅜ to ½ inch	Present joint openings: Open full width	Remarks
		Inches	*Feet*		*Percent*	*Percent*	*Percent*	*Percent*	
100–A	1925	1	94	Special	56	31	13	0	Joints filled near pavement edges with a compressed soil.
113–B	1926	1	98	None	37	42	21	0	Do.
116	1924	¾	50	do	60	25	15	0	Do.
101	1924	¾	108	Special	0	0	100	0	Do.
139–E	1931	1	91	Wire fabric	0	0	100	0	Joints filled near edges with a compressed soil.
91	1923			None					No expansion joints.
91	1931	1	91	Wire fabric	0	0	100	0	Joints filled near pavement edges with a compressed soil.
89–D	1924	¾	88	None	67	22	11	0	Do.
95–DF	1926	1	90	do	40	35	25	0	Do.
73–A	1925	1	84	do	50	30	20	0	Do.
73–A	1935	1	50	Wire fabric	0	0	0	100	Joints free.
50–A	1923		132	Special	100	0	0		Some joints are open slightly, but these were filled with a very hard formation.
50–A	1933	1	98	Wire fabric	0	0	0	100	Joints free.
70–D	1925	1	176	Special	53	40	7	0	Joints filled near pavement edges with a compressed soil.
70–D	1932	1	91	Wire fabric	0	0	0	100	Joints still free, but some sand had entered.
131–C	1930	1	94	Fabric in part	0	32	36	32	Joints filled near pavement edges with a compressed soil.
97–A	1924	¾	91	None	100	0	0	0	Some joints were open slightly, but these were filled with a compressed soil.
97–A	1928	1	100	Fabric in part	0	73	27	0	Joints filled near pavement edges with a compressed soil.
41–R	1931	¾	49	Wire fabric	0	0	0	100	Do.
150–D	1932	1	100	do	0	0	0	100	Some of the joints were free, while others were filled near the pavement edges with compressed soil.
146–B	1925	1	90	None	68	21	11	0	Joints filled near pavement edges with a compressed soil.
187–E	1918		72	do	0	0	100		Do.

[1] These observations were made during the summer
[2] For details see tables 1 and 2.

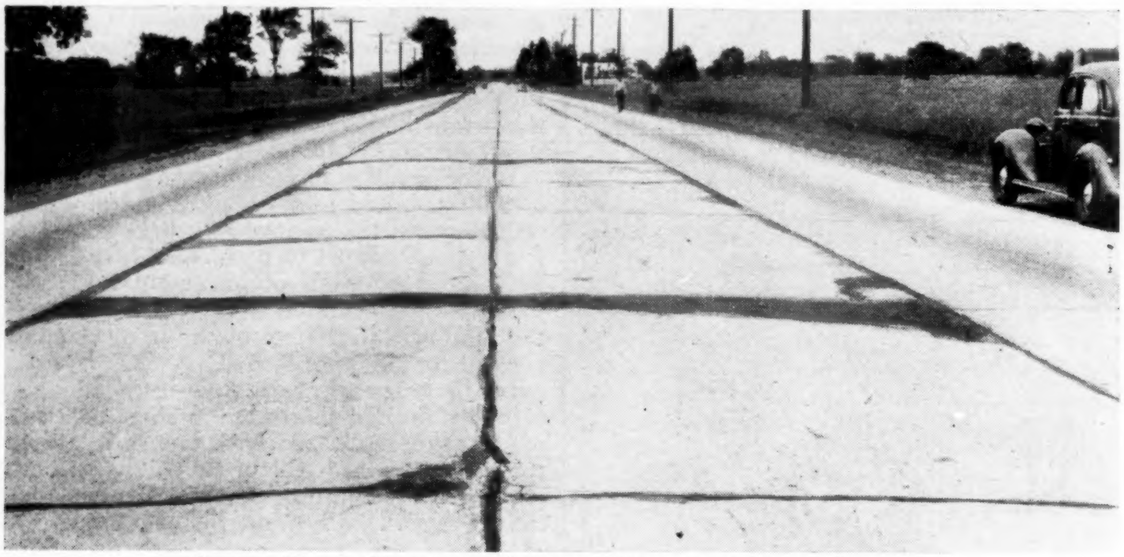

FIGURE 18.—A SECTION OF PAVEMENT TYPICAL OF THOSE STUDIED.

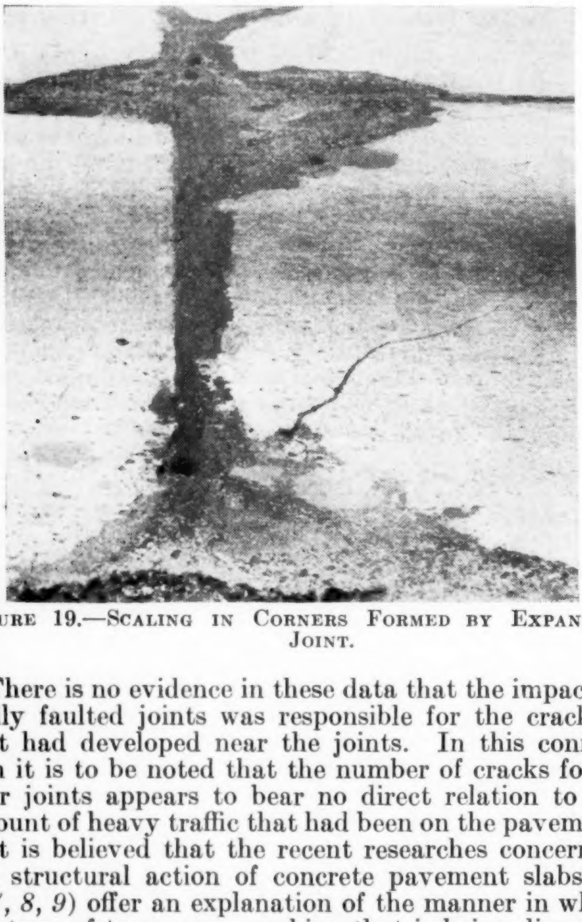

FIGURE 19.—SCALING IN CORNERS FORMED BY EXPANSION JOINT.

There is no evidence in these data that the impact at badly faulted joints was responsible for the cracking that had developed near the joints. In this connection it is to be noted that the number of cracks found near joints appears to bear no direct relation to the amount of heavy traffic that had been on the pavement.

It is believed that the recent researches concerning the structural action of concrete pavement slabs (*5, 6, 7, 8, 9*) offer an explanation of the manner in which the type of transverse cracking that is being discussed occurs.

Published reports (*5, 6, 7, 8, 9*) show that the critical stresses in concrete pavement slabs are combinations of tensile stresses from wheel loads with tensile stress already present because of restrained warping. It will be found, by a study of the distribution of the stresses caused by restrained warping that the magnitude of the important longitudinal warping stresses is relatively low near the joint edge but increases to approximately a maximum at a distance of 8 to 10 feet from the slab end. These maximum longitudinal warping stresses cannot combine with the maximum stress caused by impact of a wheel load at a faulted joint because the two do not coincide in position. It is suggested by the warping data however that the longitudinal warping stresses combined with the stresses produced by heavy wheel loads applied 8 or 10 feet from the joint may be the cause of the transverse cracks that so frequently develop at this distance from the slab ends.

The longitudinal cracking in the pavements studied apparently could be divided into two types. Cracks of the first type had developed near the edges of the pavement and did not appear to have been caused by any stress condition that should normally be present in concrete pavements. This type of defect is discussed later under the heading "infiltration cracks." Cracks of the second type were found at or near the longitudinal center line of the pavement lanes and appear to have been caused by stresses that are to be expected in concrete pavements.

The amount of this type of cracking per mile per lane of pavement for the different projects is shown in table 8. In preparing this table a crack was considered as being longitudinal if its direction did not depart more than 45° from the longitudinal axis of the pavement. All of the projects studied except 187–E had a longitudinal center joint.

The table shows that the only project with a serious amount of longitudinal cracking was 187–E. This is the 16-foot pavement laid in 1918 without a longitudinal center joint. There were 5 other pavements in which the amount of longitudinal cracking per mile exceeded 100 feet, or 2 percent of the total length. These were all old pavements built between 1923 and 1926 inclusive. The longitudinal cracking in these pavements consisted generally of short longitudinal cracks between two transverse cracks or between a transverse joint and a transverse crack. Others appeared to start from a joint or crack and extended a short distance in a direction approximately perpendicular to the joint or crack. There were other longitudinal cracks that appeared to have been caused by frost action.

There was not enough longitudinal cracking to justify definite conclusions regarding the influence of the type of subgrade or the type of pavement cross

section. It was noted, however, that a greater amount of longitudinal cracking had occurred in the pavement laid on sandy type subgrades. The reason for this is not known.

GENERAL CONDITION OF THE JOINTS DISCUSSED

Table 9 is a general summary of the condition of the joints in the various sections of pavements surveyed. The data are based on a detailed examination of five to eight typical joints per mile of pavement, or approximately 12 percent of the total number of joints in the pavement. As a part of this examination the shoulder material was dug away from the edge of the pavement at the joint for the full depth of the pavement. A surface examination was made of many other joints and they were found to be in approximately the same condition as those examined in detail.

Measurements of the widths of the joint openings were made during the hot weather of midsummer when the pavement was expanded. The temperature of the pavement at the time these measurements were made had little effect on joint openings in the plain concrete pavements because they had cracked into relatively short slab lengths. In the reinforced pavements, however, the widths of the joint openings were more responsive to changes in the temperature of the pavement and this fact should be considered in interpreting the data of the table.

On two pavements 100 percent of the joints were classified as closed and on eight pavements 50 percent or more were similarly classified. These pavements were built before 1926 and showed many transverse cracks. Five of the eight were not reinforced while the remainder had special reinforcement in certain parts of the pavements.

There were four projects (101, 139–E, 91, and 187–E) where 100 percent of the joints were open between three-eighths and one-half of an inch. Of the part of project 101 that was surveyed, approximately one-fourth was reinforced with special reinforcement (see table 2), and of the remaining three-fourths, a large part contained ¾-inch edge bars running continuously through the joints. It is possible that there was sufficient bond between the edge bars and the concrete to prevent free slippage and that the bars had a tendency to hold the cracks closed, and the joints partly open. Project 187–E was plain concrete pavement built in 1918. It was, therefore, surprising to find the joints open as much as they were. The explanation may lie in the relatively small amount of transverse cracking that had developed in this pavement.

There were five pavements, in which all of the joints were found to be open a normal amount for the temperature at the time of the survey. These were all relatively new pavements reinforced with a 60-pound wire fabric.

It is indicated by the data in table 9 that the most important cause of the closing of the expansion joints on the plain concrete pavements studied was the formation and the subsequent opening of transverse cracks. Permanent growth of the concrete may have been present but it is not possible to determine its extent from these data.

As indicated in the last column of this table, the openings that remained at the expansion joints were usually filled near each pavement edge with tightly compressed soil. This condition appeared to be worst in pavements having granular material on the shoulders and the density of the foreign matter seemed to be greatest near the edges of the pavement slabs. The foreign material in the joints of old, badly cracked pavements was particularly dense.

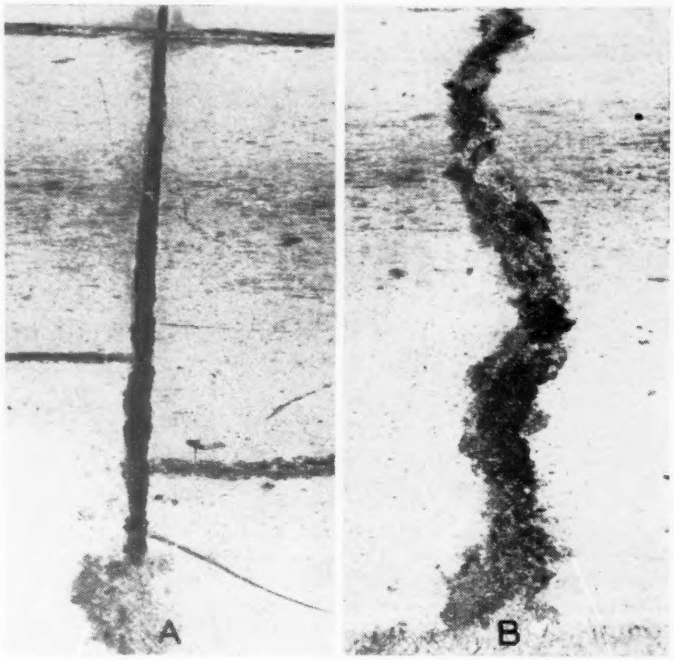

FIGURE 20.—A, NORMAL JOINT IN A TYPICAL OLD PAVEMENT; B, NORMAL CRACK IN A TYPICAL OLD PAVEMENT.

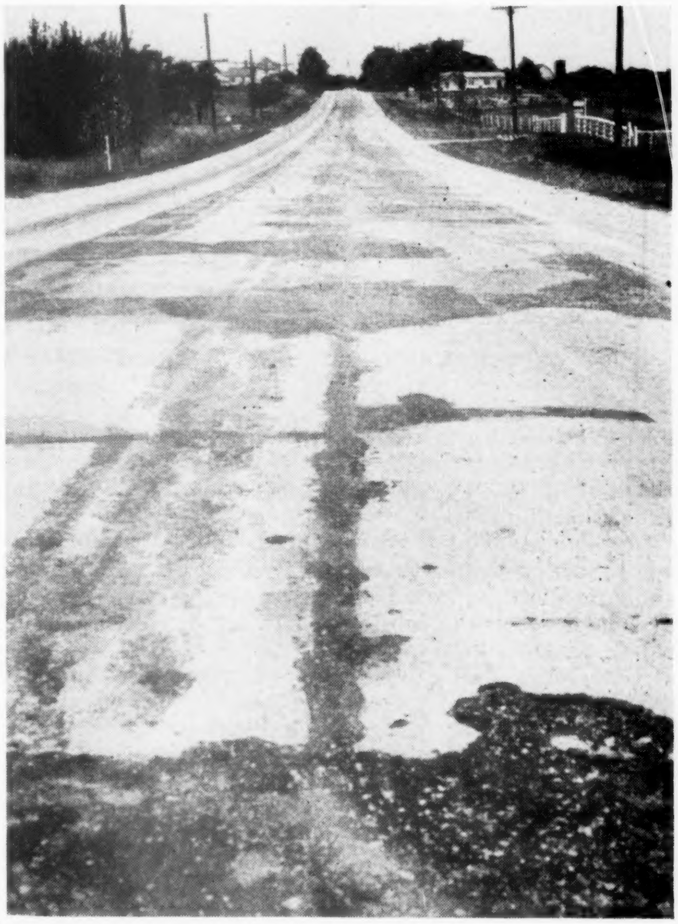

FIGURE 21.—A BADLY SCALED AND DISINTEGRATED PAVEMENT.

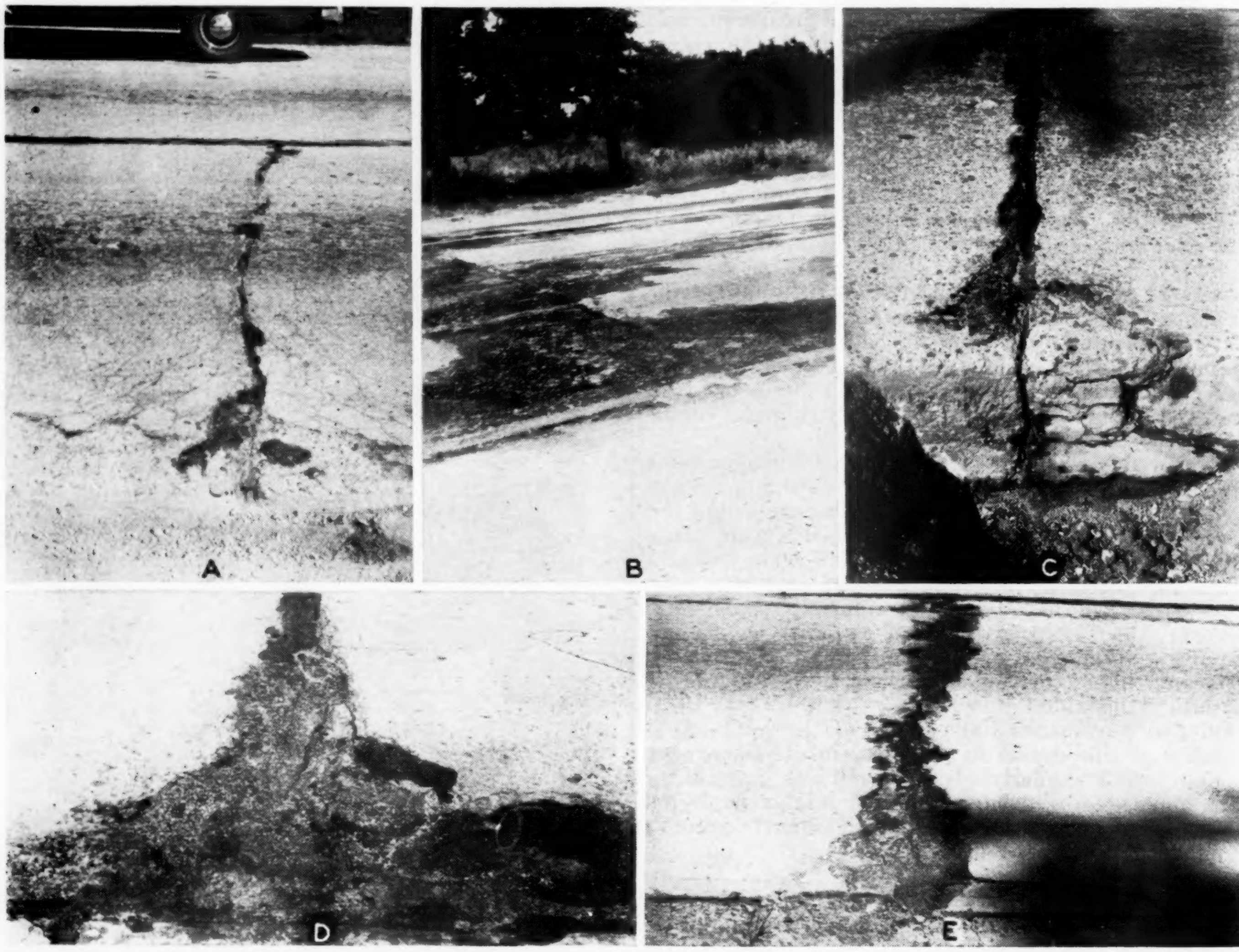

FIGURE 22.—A, SURFACE DISINTEGRATION AT CORNERS FORMED BY CRACK; B. SCALING AT CORNERS FORMED BY JOINT, COVERED WITH CRACK FILLER; C, SMALL CORNER FAILURE AT CLOSED EXPANSION JOINT; D, SCALING AT CORNERS FORMED BY CRACKS COVERED WITH CRACK FILLER; AND E, SMALL CORNER FAILURE AT CORNER FORMED BY CRACK.

The more recently built pavements in Michigan have been reinforced and the joints have been filled with an impregnated fiber joint filler. There is indication that these changes will improve the functioning of the expansion joints.

On a number of the projects the gravelly shoulders were slightly higher than the pavement. Some of the shoulder material found its way on to the pavement and eventually into the joints. Lowering of the shoulders would possibly help to prevent infiltration.

The conclusion to be drawn from this study is that if the normal widths of the expansion joints are to be maintained it will be necessary either to eliminate cracking or to place sufficient reinforcement to hold the cracks closed. It will be necessary also to prevent foreign material from entering the joints, particularly near the edges of the pavement.

There is one important observation in this connection. In spite of the many tightly closed expansion joints there appear to have been very few blow-ups in the pavements. Apparently the open cracks must act in some degree as expansion joints relieving the worst of the compression caused by expansion.

SPALLING, SCALING, AND OTHER DAMAGE AT JOINTS AND CRACKS

A pavement typical of those studied is shown in figure 18. The inside lanes of this highway were approximately 13 years old and the outside lanes were approximately 4 years old.

The dark areas on the pavement in this and other photographs, are as a general rule areas where the surface had scaled or disintegrated and repairs have been made with bituminous mixtures. This illustration shows that the damage to the old pavement is most evident in the vicinity of the corners formed by the joints and cracks. A close-up view of this condition is shown in figure 19. This is representative of one of the more badly scaled joints in a pavement in average condition for an age of 13 years.

Close-up views of a joint and a crack typical of those on one of the older pavements examined are shown in figure 20. This surface was in better than average condition for pavements of the older group. Some spalling can be noted along the edges of both the joint and the crack. It is typical that the extent of the spalling was greater at the crack than at the joint.

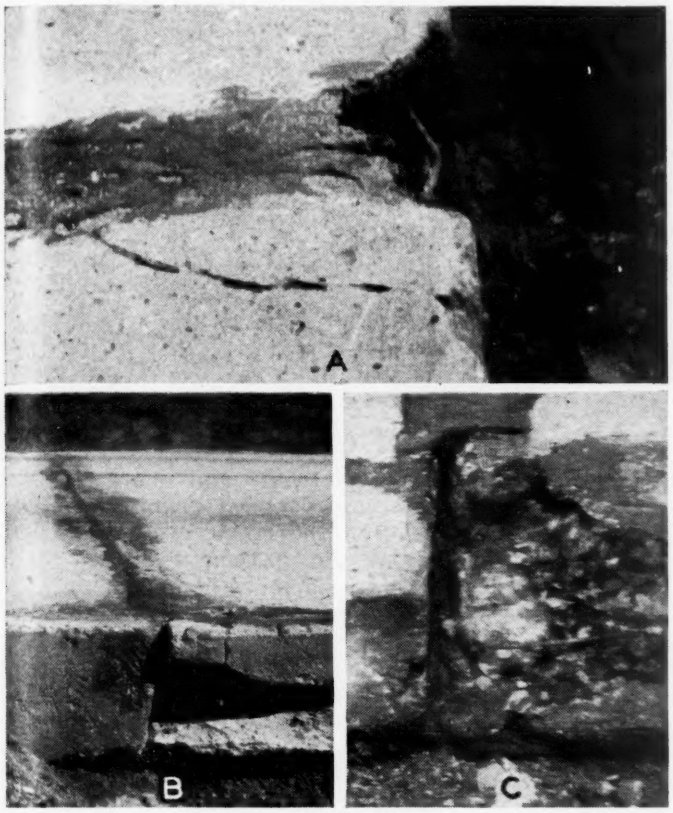

Figure 23.—A, Buckled Edge Bar of a Small Corner Failure; B, Small Corner Failure at a Joint; C, Small Corner Failure on Relatively New Reinforced Pavement.

A general view of one of the more badly scaled and disintegrated pavements is shown in figure 21. The center and right lane of this pavement were approximately 13 years old, while the left lane was relatively new. The new pavement was in good condition. The scaling and disintegration on the old surface was largely in the vicinity of joints and cracks and especially in the corners formed by the joints and cracks. Figures 22, A, and 22, D show in detail the character of the disintegration which has developed at some of the more badly damaged areas at a crack. Figure 22, B shows similar areas at a joint where bad disintegration had developed.

CAUSES OF INFILTRATION CRACKS EXAMINED

On all of the pavements the greatest part of the scaling and disintegration was in the vicinity of joints and cracks, and it apparently starts at and spreads from these points. It was observed also that there was a greater tendency for this type of deterioration to develop at cracks than at joints.

A large number of small corner breaks, of the type shown in figures 22 and 23 were found in a number of the pavements. That in figure 22, C is typical of those found at closed joints in plain concrete pavements. These failures apparently were caused by high compression at the corners, when the pavement was in an expanded condition.

The corner breaks shown in figures 22, E and 23, B are typical of a number found at the joints and cracks in the pavements of projects 116 and 91. In both of these pavements continuous plain round edge bars were used. On project 116 expansion joints were spaced at intervals of approximately 50 feet, while on

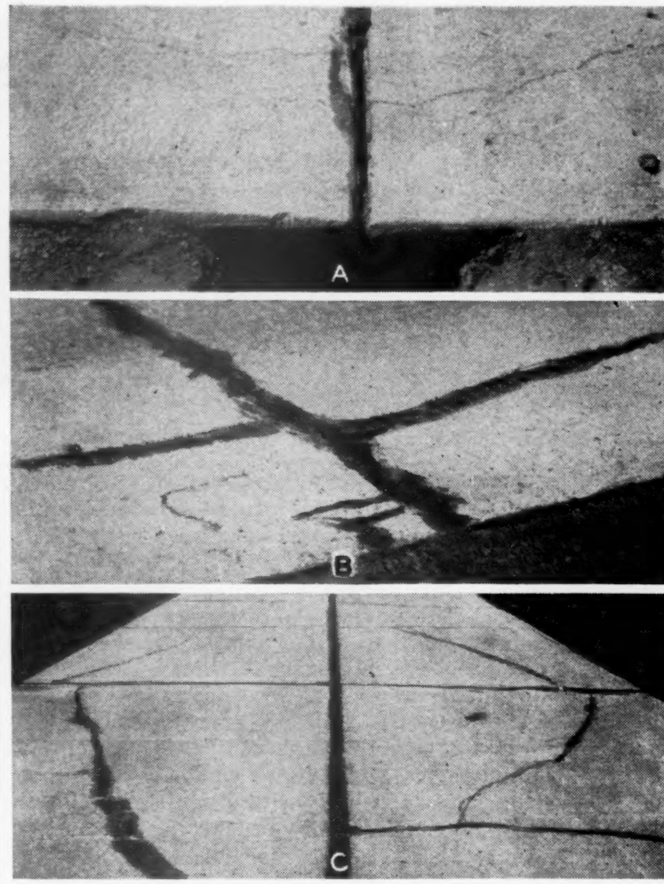

Figure 24.—A, Infiltration Crack in Early Stage of Development in Reinforced Pavement; B, Typical Infiltration Crack; C, Typical Infiltration Cracks That Have Developed to a Serious Degree.

project 91 there were no expansion joints. At a number of corner breaks on these two pavements, an examination showed that the edge bars had buckled and apparently caused the corners to fracture. A close-up view of one of these buckled bars is shown in Figure 23, A. The edge bars in this pavement were in continuous bond and extended across the expansion joints with no provision for relative movement of the steel with respect to the concrete at these joints.

The corner breaks shown in figure 23, C is typical of a large number found in the relatively new reinforced pavement of project 139–E. This joint was open approximately one-half inch but near the edges of the slab it was filled with a tightly compacted sand formation. Apparently breaks of this type were caused by highly localized compression at the corners when the pavement was expanded. The failure indicates the importance of keeping the joints free of foreign matter even in reinforced pavements. It is true that the reinforcement tends to hold the cracks closed and in this way helps to retain the normal width of the joint, but if the cracks are held closed and the joint becomes filled with incompressible foreign material the reinforced pavement may be restrained more than a plain concrete pavement.

"Infiltration crack" is a name that has been applied by engineers of the Michigan State Highway Department to a peculiar type of cracking found in many of the concrete pavements in Michigan. Figure 24 shows photographs of typical infiltration cracks.

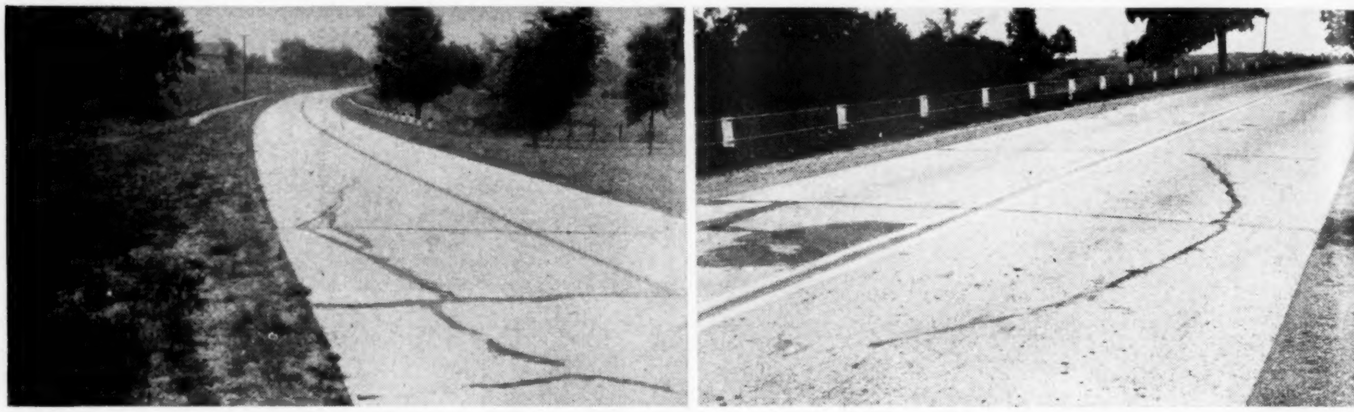

FIGURE 25.—INFILTRATION CRACKING ON STATE PROJECT 3924 C-1.

Figure 24, A shows an early stage of development. Figure 24, B shows a more advanced stage while figure 24, C shows a number of these cracks that have developed to a serious extent.

Cracks of this type generally start as a longitudinal crack, but have a tendency to progress toward the longitudinal joint in a curvilinear path. In the pavement examined, it was found that the cracks almost invariably begin at transverse joints at a point near the edge of the pavement, the distance from the edge being generally somewhere between 8 and 36 inches.

The Michigan State Highway Department had made an earlier study of this type of cracking and found that the joints at which these cracks occurred were filled for a short distance near the edges of the pavement with a hard compacted formation of earth that had filtered in from the shoulders. With the outer ends of the joint tightly filled, part of the pavement has room in which to expand while the other part along the pavement edges is restrained. Thus, there may be a tendency for a splitting or shearing action at the joints as the pavement expands.

Among the pavements selected for study of joint conditions, the greatest number of infiltration cracks were found on projects 101, 95–DF, 146–B, 91 (old), and 139–E. All of these, with the exception of 139–E, were plain concrete pavements constructed before 1927. The pavement on project 139–E was a reinforced pavement laid in 1931 and on it infiltration cracks were in a very early stage of development. Two of the pavements had edge bars and three did not. All of the pavements with an appreciable number of these cracks were laid on a sandy subgrade and, as in the earlier Michigan investigations, it was found that the joints at which these cracks occurred, were filled near the edges of the pavement with compressed earth.

Development of these cracks was not serious on any of the pavements included in the formal study. The greatest number was found on project 95–DF. This pavement was built in 1926 and at the time of the survey, there was an average of 13 such cracks per lane-mile. The cracks had an average length of approximately 8 feet and had not created a serious condition.

A special study was made of one pavement on which the condition caused by this type of cracking had become somewhat more serious. This was a State project on route M–89 between Battle Creek and Gull Lake a plain concrete pavement built in 1930. It was located on a sandy subgrade of group A–3. There was no heavy commercial traffic and general traffic was light. Figure 25 show typical examples of the infiltration cracks. Often the cracks were wide and they greatly weakened the pavement. They were found at intervals over the 5 miles of pavement with the exception of short sections that were densely shaded.

It is of interest to examine the data for evidence, as to the correctness of the theory that the impacted material at the joint ends is responsible for the formation of the infiltration cracks.

While it is true that those joints at which these cracks had developed were found to be tightly packed with soil material near the pavement edges, it is also true that this was a more or less common condition in the older pavements and many joints that were filled with earth had not developed these cracks.

Joints containing compressed soil near the pavement edges were found on both clay and the sand subgrades yet the type of cracking being discussed was largely confined to pavements on sandy subgrades. It is possible that the material in the joints of the pavements on clay was not as dense as that in the joints where sandy material obtains but a careful examination in the field of the compacted material of both types failed to show any noticeable difference. It is possible that a difference in compressibility was not revealed by the field examination.

It might be expected that high compression against the ends of two abutting slabs would, if confined to a small area, result in a spalling or shearing failure at the extreme corners. Examination of a great many corners at joints where infiltration cracks had occurred disclosed only a few such failures.

Figure 26 was prepared to study the possible effect of combined load and temperature warping stresses in causing infiltration cracks. The load stresses were obtained by applying a static load at points 1 foot apart across the free end of a pavement slab. These stresses are the averages obtained from tests on several slabs. In each case the center of the loaded area was placed 9 inches from the end of the slab and the critical stress was measured directly under the load in the direction parallel to the joint. The warping stresses were measured at corresponding points also in a direction parallel to the transverse joints at a time when the warping stress conditions were critical.

It is believed that the stresses shown by the curves of this figure are typical of those existing across the ends of slabs having a width of approximately 10 feet

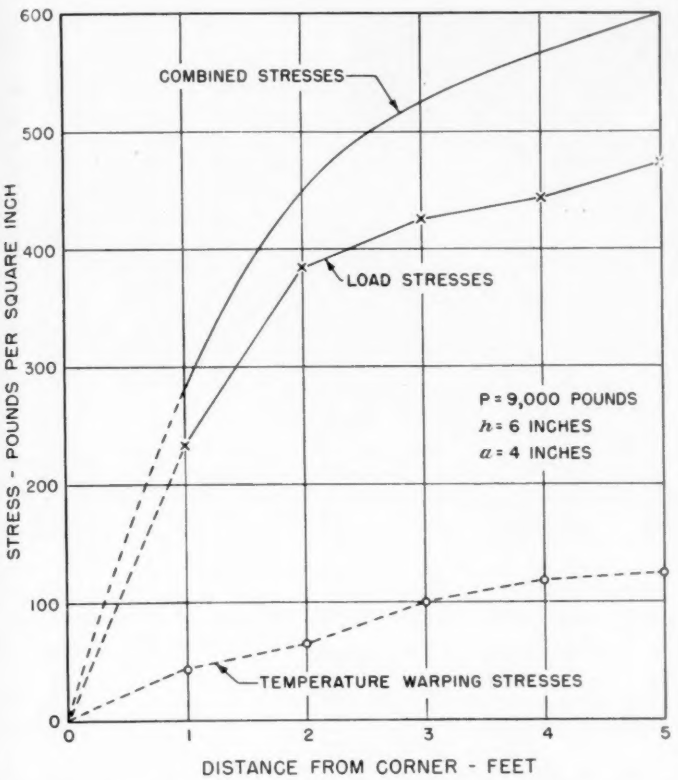

Figure 26.—Typical Combined Load and Warping Stress Curve Across Free End of Pavement Slab.

and with no provision for load transfer. It is evident that for the conditions described, the load stresses are far more important than the warping stresses.

The combined stresses are relatively low near the edges of the pavement, but increase with the distance from the corner. At distances greater than 2 feet from the edges, the combined stresses are higher than is desirable. Wheel loads of the magnitude used in these tests (9,000 pounds) moving in a normal position can create high combined stresses in that part of the slab end where many of the infiltration cracks begin. From this it might be assumed that combined load and warping stresses are the cause of the cracks, were it not for the fact that some cracks have their origin approximately 8 inches from the edge of the pavement and figure 26 indicates that the combined stresses are definitely low in this region. Also the pavement with the greatest number of these cracks and on which they have progressed to the greatest degree carried only light traffic. It appears that combined load and warping stresses, while they may contribute to the stress condition that causes the rupture, can hardly be the sole cause.

It seems more likely that failure may be due to a complex stress condition produced by a combination of forces derived from wheel loads, warping restraint, and the eccentric expansion against a partially filled expansion joint. The Michigan State Highway Department is attempting to develop a method of sealing joints that will prevent infiltration of material from the shoulders with the idea that this may prevent the development of these cracks.

Until the causes of this type of cracking are definitely established, it may be desirable to place one or two

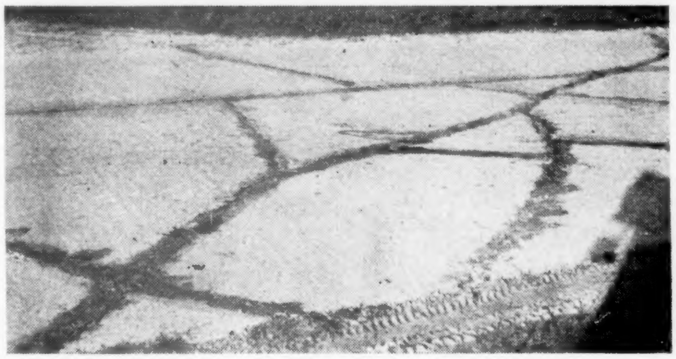

Figure 27.—Cracking Caused by Differential Frost Heaving at Interior of Pavement.

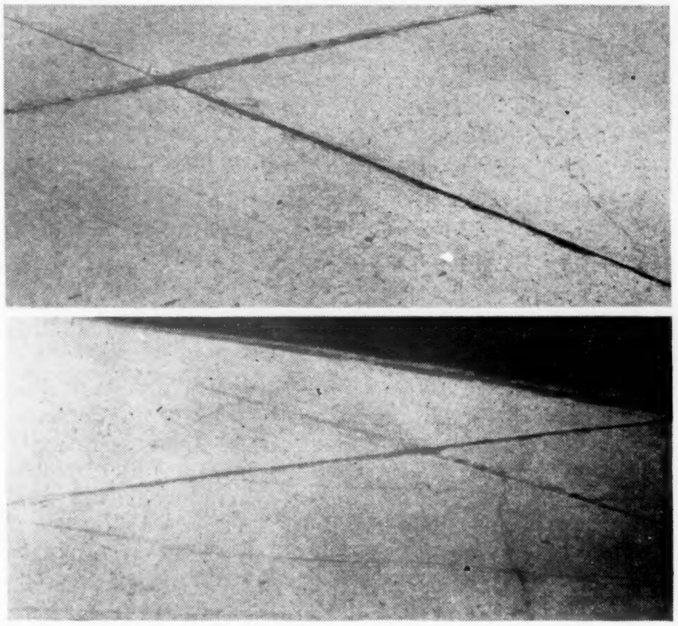

Figure 28.—Cracking Near Joints Containing Load-Transfer Devices That Resist Upward Flexure.

½-inch reinforcing bars across the end of the slab at the expansion joints in pavements placed on sandy subgrades. Such reinforcement would probably keep the cracks closed should they form.

ADDITIONAL PAVEMENTS EXAMINED

In conjunction with this general study, certain pavements not selected for detailed examination were inspected. The observations made are included in this report as general information pertinent to the subject.

The first pavements inspected in this way were located in the Upper Peninsula. They had been built within the preceding 3 or 4 years and all of them contained joint devices that permitted free downward bending but seriously restrained upward bending at the joint.

In the past, trouble with differential frost heaving had been experienced in the subgrades of pavements in the Upper Peninsula. Considerable effort was being made to prepare the subgrades for new pavements in a manner to avoid this trouble, but the steps taken apparently had not been entirely successful.

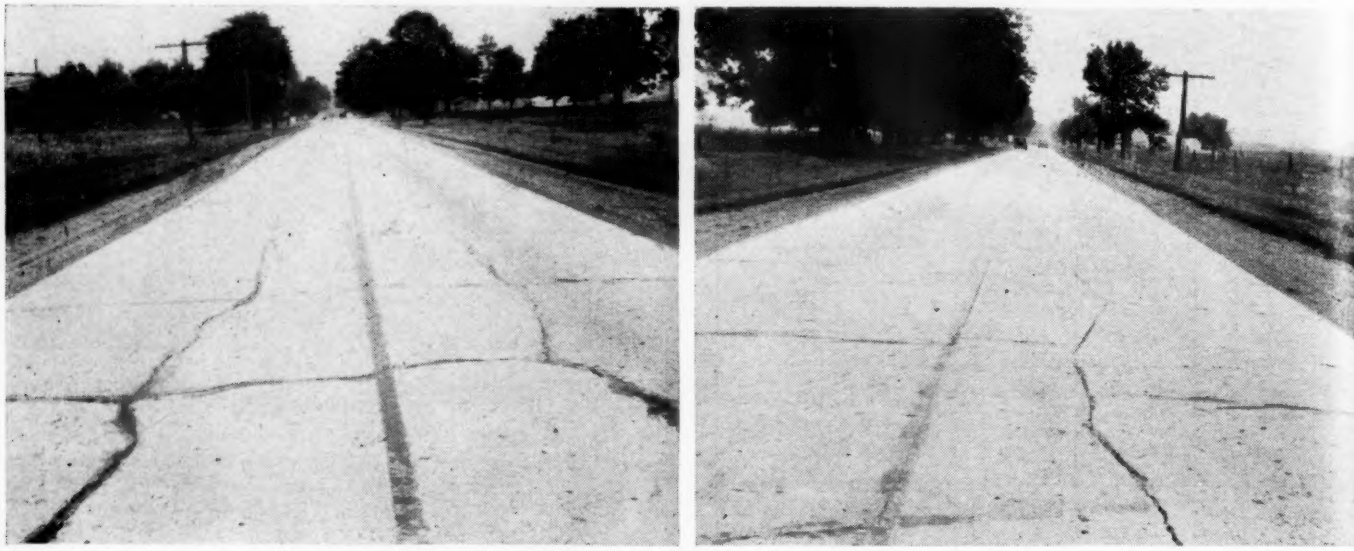

FIGURE 29.—LONGITUDINAL CRACKING IN PAVEMENT WITH RIGID LONGITUDINAL JOINT.

RIGID JOINT DEVICES MAY CAUSE CRACKING

Figure 27 shows a typical pattern of cracking where differential frost heaving had occurred under a slab in an area away from a joint. The pattern of cracking which developed from the same cause in the vicinity of a joint appeared to be different, depending upon whether the joint had a load-transfer device and varying with the type and rigidity of the device.

When the joints do not have load-transfer devices, the ends of the adjoining slabs are free to move vertically and independently of each other. This frequently results in high or badly faulted joints, but it prevents development of certain stresses when heaving occurs.

Frost heaving beneath free transverse joints, if sufficiently severe, causes simple transverse cracks to form near the joints but apparently does not cause the very irregular diagonal and crisscross fracture that results from severe frost heaving under the slab interiors. On the sections of pavement that were studied intensively a number of cases were noted where frost heave had broken the interior area of a slab in the manner shown in figure 27. Such failures were not observed near the free joints although it was reported that certain of the joints examined were known to have been severely heaved by frost action in previous winters. The slabs at these points were cracked transversely near the joints but no other cracking was observed.

When load-transfer devices of a type that resists joint flexure are used at transverse expansion joints, differential frost heaving causes cracking in the vicinity of the joint similar in pattern to that which develops at the interior of a pavement slab. Two joints that illustrate this action are shown in figure 28. Figure 28, A shows a joint on FAP 265–B, while figure 28, B shows a similar one on FAP 163–F. Both of these were new reinforced pavements and, when inspected, the cracks were being held closed by the reinforcement.

Another type of cracking observed during the general inspection of certain pavements is that shown in figure 29. The longitudinal cracks developed along each side of the longitudinal joint and were continuous over a large part of the total length of the pavement. This type of cracking was investigated in Wisconsin (*2*) and was found to be associated with a soil in which frost heaving occurs and also with close spacing of tie bars across the longitudinal joints. The longitudinal joints in the Wisconsin pavements in which this type of cracking had occurred were of the tongue-and-groove type with tie bars spaced 24 inches. This type of cracking was not found in pavements that were similar with the exception of a tie bar spacing of 48 inches.

The longitudinal joint used in the Michigan pavement in which this type of cracking was observed is of the tongue-and-groove type with tie bars spaced at 20 inches. It is quite possible that the cracking was in some measure caused by the rigidity at the longitudinal joint which resulted from the use of a relatively large amount of tie steel.

In the Arlington investigation of the structural behavior of concrete pavements, (*5, 6, 7, 8, 9*) it was found that some of the most important stress conditions in pavement slabs of normal thickness and normal size are those in the longitudinal direction of the pavement caused by variations in the temperature and moisture condition of the concrete. Of these two it seems probable that the more important are the stresses caused by restrained warping when a large temperature differential develops in the pavement. At such times the warping stresses are most critical. In certain parts of the slab the tensile stress from restrained warping combines with the tensile stresses caused by loads and the resultant stresses are frequently very high, considerably higher than is desirable as a working stress. The practical implications of these combined stresses have been quite thoroughly discussed in two comparatively recent papers (*1, 3*).

LOAD TRANSFER AT JOINTS DESIRABLE TO PREVENT FAULTING

The warping stresses increase with an increase in the length or width of the slabs up to a point where the dimension of the slab is sufficient to effect complete restraint. For example, in a long narrow slab the warping stresses are high in the longitudinal direction but low in the transverse direction. In very short narrow slabs the warping stresses are low in both directions. Except in very small slabs, the magnitude of the load stresses is not greatly affected by the size of the slab. The magnitude of the load stress is affected however by the distance between the center of load application and the edges of the slab. For

example, directly under a load applied at the extreme edge of a slab the stress in the direction perpendicular to the edge is zero. This same load applied at a distance of approximately 3 feet from the edge causes a stress approximately equal to that which would be caused if it were applied at the interior of a large slab.

Westergaard has shown by theory that when load stresses alone are responsible for the cracking of a concrete pavement slab the tendency is for the slab to break down into pieces that are approximately 3 to 4 feet square (*10*). Researches of the Public Roads Administration have indicated that normal wheel loads alone should not be expected to cause critical stresses in slabs of 7 inches or more in thickness. It is only when the stress from a wheel load combines with a stress from restrained warping that the combined value reaches a magnitude that may rupture the slab. If the dimensions of the slab are reduced by closer spacing of joints the magnitude of the warping and hence of the combined stresses is reduced. Experience shows that if joints are not provided, pavements tend to break down into relatively small units.

Both the load stresses and warping stresses are affected by the thickness of the pavement. Other conditions being equal, load stress increases as the thickness of the pavement is reduced, while in slabs of appreciable length the warping stress decreases.

When consideration is given to the stresses in concrete pavements resulting from wheel loads and temperature variations, it is reasonable to assume that a large percentage of the transverse cracking in long slabs is caused by critical combinations of load and warping stresses. This appears to explain the presence of the transverse cracks often found near the expansion joints as well as those at greater distances from the joints. Other transverse cracking may be caused by frost action or settlement of the subgrade.

The cause of infiltration cracking is not definitely known, but there is strong evidence that this form of cracking is not caused by the load stresses alone.

The warping stresses are low in the vicinity of free corners of pavement slabs. Therefore, it is reasonable to believe that corner breaks, involving relatively large areas, are caused largely by the load stresses.

There is a present tendency to use for load transfer in the joints, devices designed primarily to give high shearing resistance when loads are applied on one side of the joint. Sometimes these load-transfer devices are designed without regard to the effect they may have on stresses near the joints from causes other than loads. A realization of the importance of other stress conditions is necessary if a joint structure is to be properly designed.

In the report of the Arlington investigation (*8*) it was concluded that the main functions of joints in concrete pavements are to permit the pavement to expand, contract, and warp freely. Load-transfer devices and devices to hold the two sides of a joint in a common plane should be designed to correct certain weaknesses at the joint edges of the pavement and should be designed in a way which will not interfere with the main functions of a joint.

Another function of joints in concrete pavements and one that is not often stressed is to give to the pavement sufficient flexibility for adjustment to changes in the shape of the subgrade. A differential settlement or heaving of the subgrade of only a fraction of an inch will leave a portion of a completely rigid pavement unsupported by the subgrade. Such a condition is especially apt to develop on subgrades subject to large or irregular volumetric changes with freezing or with changes in the moisture content. If the pavement contains a sufficient number of properly designed, sufficiently flexible joints, it is obviously free to adjust itself to the changed condition of the subgrade without serious cracking.

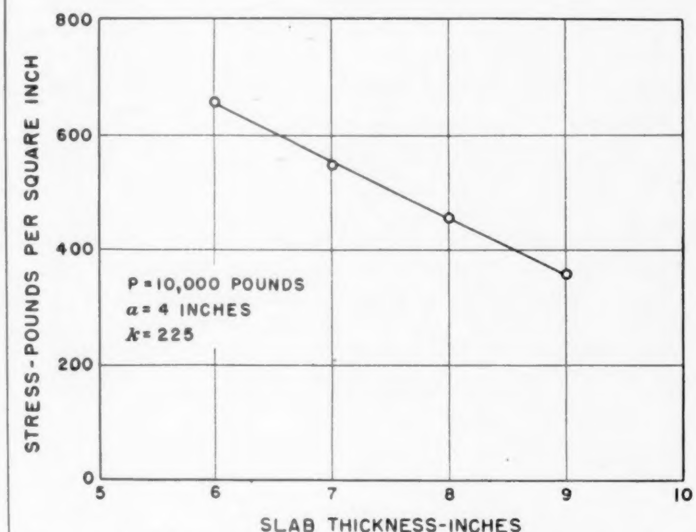

FIGURE 30.—COMBINED LOAD AND WARPING STRESSES MEASURED AT THE EDGES OF FREE TRANSVERSE JOINTS. THE LOAD STRESSES WERE MEASURED DIRECTLY UNDER THE LOAD IN THE DIRECTION PARALLEL TO THE JOINT EDGE. THE WIDTH OF THE SLAB WAS 10 FEET.

The depth of a slab of uniform thickness is determined generally by the stress conditions at the edges or weakest part. For this reason it has been concluded (*3*) that edge strengthening is not necessary at the edges of adequately designed uniform-thickness pavements. The interior depth of a thickened slab should be determined by the stress conditions at the interior or strongest part of the pavement. Therefore, in such a pavement the transverse edges formed by joints and cracks are a source of potential weakness unless provision is made for strengthening them. A load-transfer device is frequently used for this purpose.

Sometimes, because of an arbitrary selection of cross section the interior thickness of a thickened-edge pavement may be greater than is necessary to satisfactorily resist the combined stresses at the interior. In such cases the stresses along transverse joint edges from combined load and temperature effects may not be excessive and stress reduction through edge support may not be necessary. However, this is true only for slabs with relatively great interior thickness.

To study this condition the combined load and warping stresses were measured at the edges of free transverse joints in slabs of four different thicknesses. These stresses are shown in figure 30. The warping stresses were measured under critical temperature conditions. The load stresses were measured directly under a load of 10,000 pounds in the direction parallel to the joint. The subgrade under this pavement was a silty loam of group A–4.

These data show that the combined load and warping stresses, at the transverse edges of a free joint, decrease as the thickness of the pavement is increased. This is because the width of the pavement slabs on which these stresses were measured was only 10 feet, and the warping stresses in the transverse direction of slabs of this

width are not large. The magnitudes of the combined load and warping stresses at the edges of free joints in slabs of different thicknesses, depends, therefore, very largely upon the magnitudes of the load stresses.

Concrete of the class generally used in pavements has a transverse bending strength ranging approximately from 600 to 1,000 pounds per square inch. It is apparent that the stresses shown in figure 30 for the 6- and 7-inch slabs are higher than desirable, but the stresses for the 8- and 9-inch slabs are no higher than the combined stresses which frequently occur at the interior of slabs of normal size and thickness.

The data obtained in the survey show that faulting has occurred at the joints of the majority of the pavements investigated. While the severity of the faulting appears to be influenced to some extent by the type of subgrade material, it was found that faulting had developed to an undesirable degree on all types of subgrades observed. Some faulting was found at cracks, but the severity at cracks was definitely less than at joints.

If the smoothness of the pavement surface at joints is to be maintained, provision must be made to insure the maintenance of the slab alinement and this will be as necessary for pavements of uniform thickness as for those with a thickened edge.

Devices for connecting the ends of abutting slabs at an expansion joint thus divide themselves into two classes: first, those whose function is to maintain surface alinement and reduce the critical edge strains and, second, those whose sole purpose is to maintain the surface alinement.

Load-transfer devices of the first class are the most troublesome since the requirements for a satisfactory design are more severe. The general principles of action of this type of joint have been discussed in some detail in the report on the Arlington research (*8*). Further research is needed to provide additional information concerning the efficacy of some of the designs that have been used or proposed for use.

In the second group, where reduction in critical slab stresses is not a consideration, the problem of designing suitable units is less complex, but even so, there are essential requirements that must be taken into account. For example, the device must provide sufficient strength to resist the forces that tend to produce faulting without introducing serious restraint to slab warping.

SUMMARY AND CONCLUSIONS

The primary object of this study was to determine if possible whether the condition of the pavements indicated a need for load-transfer devices at transverse joints. The method was to examine typical sections of selected pavements for (1) evidence of structural weakness in the vicinity of transverse joints and (2) evidence of other undesirable conditions attributable to the absence of structural connection between the ends of abutting slabs. Certain collateral information has been developed and observations concerning this have been included.

In considering the evidence, it should be kept in mind that the pavements selected for study in general were old pavements on the more heavily traveled routes and the transverse joints had no provision for load transfer. The thicknesses of the interior portion of the pavements selected for detailed examination were 7 inches or more.

Evidence of structural weakness in the vicinity of transverse joints.—Pavement slabs, like other structures, show evidence of structural weakness by cracking under the action of the forces to which they are subjected. Hence, the character of the cracking found in pavements that have been in service for some time, indicates rather clearly whether the pavement is strong enough to resist the forces normally to be expected. In such an examination, it is necessary to distinguish between normal and abnormal conditions of stress.

The indications that bear on the structural weakness in the vicinity of joints are:

Corner breaks.—Failures at slab corners are of two types. One is associated with structural weakness and in failures of this type, a wheel load applied in the corner region breaks off a considerable area of the slab corner in a manner that is characteristic and readily recognized. Failures of this type were almost completely absent in the pavements examined.

The other type of corner failure is not associated with structural weakness. It was rather prevalent and will be mentioned later.

Longitudinal cracks.—Longitudinal cracks are most likely to be caused by combined warping and load stress. If a pavement is divided into articulated lanes approximately 10 feet wide the warping stress component is not large and longitudinal cracking ordinarily does not occur if the pavement is thick enough to keep load stresses within safe values. Longitudinal cracking at a transverse joint may indicate structural weakness from inadequate slab thickness or lack of edge support.

Such cracks were found in a few isolated instances, extending from a transverse joint to a transverse crack, but in general, it may be said that indications of structural weakness, as shown by longitudinal cracking were almost wholly absent from the pavements examined in detail.

Other special forms of longitudinal cracking were observed and will be mentioned later.

Transverse cracking in the vicinity of transverse joints.—Formation of transverse cracks near transverse joints has been studied carefully in the field and has been analyzed from the standpoint of critical combined stresses.

It was found that the number of transverse cracks near the transverse joints is approximately the same on the approach slabs (in the direction of traffic) as it is on the slabs beyond the joints. This condition is about the same on pavements with a large number of badly faulted joints as on pavements with relatively small number of such joints.

The total number of transverse cracks near transverse joints was approximately the same in pavements with a large number of badly faulted joints in as those with a small number of such joints.

The data indicate that the majority of the transverse cracks that occurred near transverse joints were caused by combined load and warping stresses across the section where the crack formed and that the absence of load transfer in the nearby joint was not primarily responsible for their formation.

First conclusion.—From the evidence it must be concluded that in the pavements examined in detail in this survey, there is little evidence of structural weakness in the vicinity of the transverse joints.

UNDESIRABLE CONDITIONS ATTRIBUTED TO ABSENCE OF STRUCTURAL CONNECTION BETWEEN THE ENDS OF SLABS

Dowels and similar devices between the slab ends that come together at a joint are generally considered to have two main functions: To enable one slab end to help support the other as a load passes and to maintain the alinement of the pavement surface in the vicinity of the joint. The importance of the first function depends upon the slab design and it has already been discussed. The second function is important as it affects the smoothness, the appearance, and the structural durability of the pavement.

The faulting of joints, that is, the vertical displacement of one slab end with respect to the other, was found to be prevalent to an undesirable extent in all the older pavements examined. While it was evident in pavements on all of the types of subgrades, pavements laid on clay-type subgrade materials were found to contain the greater percentage of badly faulted joints.

The faulting found at transverse cracks was definitely less in magnitude than that at transverse joints, in fact, faulting at cracks was not sufficiently serious to constitute a problem. It is thought that both the longitudinal joint construction and the use of edge-bar reinforcement have been beneficial in maintaining slab alinement at transverse cracks. On the other hand, faulting at joints had in many cases developed to an objectionable extent and there is no doubt that, had there been some suitable structural connection in the transverse joints, the condition that existed would not have developed.

Second conclusion.—From the evidence, it must be concluded that some adequate structural connection between the ends of pavement slabs meeting at a transverse expansion joint is an essential part of a good joint design, even though the slab ends themselves are structurally adequate.

COLLATERAL OBSERVATIONS

Pavement conditions found in the course of the survey led to a number of significant observations not directly related to the primary purpose of the investigation. These are presented as information of interest and value to those concerned with the structural performance of concrete pavements.

Concrete pavements, constructed with expansion joints at intervals of approximately 100 feet and without contraction joints tend to be reduced by transverse cracking, to slab lengths of between 15 and 20 feet and the greater part of this cracking occurs during the first 4 years of pavement life.

If traffic volumes at the time of examination can be accepted as an index of the relative amounts of traffic to which they were subjected, it must be concluded that the amount of transverse cracking that ultimately develops bears little or no relation to the total number of vehicles or to the number of heavy wheel loads that pass over the pavement.

Pavements that contained distributed reinforcement appeared to be in better condition than plain concrete pavements of the same age.

The use of too much steel in the form of tie bars across a longitudinal joint may contribute to longitudinal cracking by restraining warping and by preventing proper adjustment or seating of the pavement on the subgrade in case unequal expansion or settlement occurs in the subgrade.

The defect that has been called an "infiltration crack," although not prevalent, is sufficiently frequent to merit attention. While probably not the result of any single cause, the impacted condition of the expansion joint, particularly near the edge of the pavement, is believed to be an important contributing factor. It appears that these cracks could not be caused solely by load stress.

It is important that expansion joints be maintained in a condition that permits free movement of the slab ends.

Gradual closing of expansion joints with time seems to be primarily the result of gradual opening of the transverse cracks between joints. If the normal functioning of the expansion joints is to be maintained, it appears necessary either to eliminate cracking or to use steel reinforcement to prevent openings at such cracks as form between joints.

There is evidence to indicate that an adequately reinforced concrete pavement slab requires less expansion space than one of equal size without reinforcement.

Expansion failures of the type commonly known as "blow-ups" were not found during this survey, in spite of the fact that frequently the expansion joints were closed or filled with tightly compressed soil. It is possible that the foreign matter in the joints and cracks was sufficiently yielding to prevent this type of failure.

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